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FINAL REPORT

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Anil Nerode

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13. ABSTRACT *(Maximum 200 words)*

Significant discoveries were made concerning the role of symmetry in dynamical systems, work on the dynamics of low-dimensional dynamical systems (one and two dimensional real and complex systems), and progress in the use of symbolic computation tools for the study of dynamical systems. The development of the visualization tool and interface for studying dynamical systems, kaos, was partially funded through MSI.

over

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Research in interacting particle systems increased as they are attractive models useful in a wide variety of situations in physics, biology, and image processing. One of the great breakthroughs in the subject in the past five years was R. Durrett's development of methods for treating large classes of these models if one is willing to assume that the range of interaction is large or that the particles are moving at a fast rate. These assumptions are satisfied in many biological and physical systems and provide a reliable guide to the qualitative features of other systems, as well.

Very significant work was done in the area of polytopes, generalized discriminants, and resultants. They established a conjecture of Baues arising in the geometry of loop spaces in homotopy theory.

Research and development was done on Macaulay which has become one of the major computer algebra systems for computations in algebraic geometry and commutative algebra. The system is in use world-wide. MSI-funded research ranged from the development of new, underlying theoretical mathematics to the actual implementation of the program.

Automatic techniques were developed to generate differential equations that model physical systems. The work uses symbolic computation to generate the equations and ties together symbolic and numerical methods to make the equations easier to solve.

Final Report

1. ARO proposal number	P23306-MA
2. Period covered by report	1 January 1986 - 31 January 1992
3. Title of proposal	A Center of Excellence in the Mathematical Sciences--at Cornell University
4. Contract or grant number	DAAG29-85-C-0018
5. Name of institute	Cornell University
6. Authors	Anil Nerode, John J. Chiment
7. List of manuscripts submitted or published under ARO sponsorship during this period, including journal references.	539 manuscripts have been submitted for publication under ARO sponsorship. A list of technical reports is in Appendix E.
8. Scientific personnel supported by this project and degrees awarded during this reporting period.	The following types of scientific personnel were supported:

Cornell Faculty	27
Visiting Faculty	28
Postdoctoral Associates	12
Graduate Fellows	5

Ph.D. degrees awarded to the following:

Lee Alton Barford	CS	Mar. 1987
Jerome F. Hajjar	CEE	Nov. 1987
Jonathan Louis Len	CAM	Aug. 1987
Guangxuan Li	T&AM	Aug. 1987
Wei-Min Liu	CAM	Aug. 1987
Craig Martens	Chem.	Aug. 1987
Sanzheng Qiao	CAM	Aug. 1987
Anuchet Tiranuchit	EE	May 1987
Carolyn Turbyfill	CS	Sept. 1987
Ruth Haas	OR	Sept. 1987
Christian H. Bischof	CS	Aug. 1988
Laurence Fried	Chem.	Aug. 1988
Janet Head	Math,	Jan. 1988

Ph.D. degrees awarded to the following (cont.):

Anand Jagota	ME	May 1988
John Eric Mitchell	OR&IE	Aug. 1988
M. Ravichandran	ME	Jan. 1988
Holly Rushmeier	ME	May 1988
Gregory Schenter	Phys.	May 1988
Glen Swindle	CAM	Aug. 1988
Matthew Varghese	EE	Jan. 1988
Ben Wittner	Math.	May 1988
Wai-Ho Yeung	EE	May 1988
Jinchao Yu	Math.	Dec. 1988
Lauren L. Rose	Math.	Dec. 1988
Vicki Bergman	T&AM	Jan. 1989
Douglas Campbell	CS	Aug. 1989
Claudi Czado	OR&IE	Jan. 1989
Lars Ewerbring	EE	Aug. 1989
Yuval Fisher	Math.	Aug. 1989
Sharon Johnson	OR&IE	Jan. 1989
Lisa McShane	OR&IE	Aug. 1989
Chris Nobel	Math.	Aug. 1989
Steven Plimpton	Phys.	Aug. 1989
Gerald Quinlan	Phys.	Aug. 1989
David Shallcross	OR&IE	Aug. 1989
Zhongxing Ye	CAM	Jan. 1989
Amy Briggs	CS	Jan. 1990
Andrew Forbes	OR&IE	May 1990
Neil Gershenfeld	Phys.	Jan. 1990
Samuel Howard	T&AM	Jan. 1990
Fu-Shing Hsieh	Stat.	Aug. 1990
Timothy Kiemel	CAM	May 1990
James Lipton	Math.	Jan. 1990
Claudia Neuhauser	Math.	Jun. 1990
Todd Peterson	Math.	Aug. 1990
Paul Plassmann	CAM	Jan. 1990
Ambar Sengupta	Math.	Aug. 1990
Duminda Wijesekera	Math.	Jan. 1990
Alexander Yakhnis	Math.	Aug. 1990
Valadmir Yakhnis	Math.	Aug. 1990
Mary Dowling	OR&IE	Jan. 1991
Vincent Prantil	M&AE	Jan. 1991
Erich Friedman	Math.	May 1991
Frederick Adler	CAM	Aug. 1991
Alex Maholov	CAM	Aug. 1991
Peter Swart	CAM	Aug. 1991
Mark Hanisch	CAM	Aug. 1991
Radha Jamadeesan	CS	Aug. 1991

9. Outline of research activites

We are going through a period of the mathematization of everything. The sciences and engineering are being joined to mathematics through the development and analysis of algorithms. Future improvements in computing physical and engineering models will depend as much on advances in applied mathematics and its algorithms as on computer technology. Applied mathematics will develop in response to these challenges and the development of algorithms will spur work in pure mathematics. During the five years of this contract, the Mathematical Sciences Institute has contributed to the development of emerging, cross-disciplinary areas of relevant mathematical science.

During the most recent contract year, MSI supported two special Director's programs, one Applied Analysis program, two Numerical Analysis programs, two Probability and Mathematical Statistics programs, and one Computational Geometry and Algebra program. During this period, twenty seven Cornell faculty, twenty eight visiting faculty, twelve postdoctoral fellows, five school-year graduate fellows, and eight summer graduate fellows received support. MSI-affiliated faculty and staff presented public lectures and keynote speeches and organized conferences and workshops at Cornell University and elsewhere. Lectures for the general public were organized in cooperation with the Cornell Adult University and the Cornell Office of Equal Opportunity. Support for Mathematics Awareness Week was coordinated through the Cornell Department of Mathematics.

Three MSI-affiliated, Cornell faculty received Presidential Young Investigator awards and one received an Alfred P. Sloan Research Fellowship. Anil Nerode, MSI Director, was named the Goldwin Smith Professor of Mathematics at Cornell University.

During the 1986-1992 contract period, MSI-affiliated researchers broke new ground in a number of areas:

Significant discoveries were made concerning the role of symmetry in dynamical systems, work on the dynamics of low-dimensional dynamical systems (one and two dimensional real and complex systems), and progress in the use of symbolic computation tools for the study of dynamical systems. The development of the visualization tool and interface for studying dynamical systems, **kaos**, was partially funded through MSI.

Research in interacting particle systems increased as they are attractive models useful in a wide variety of situations in physics, biology, and image processing. One of the great breakthroughs in the subject in the past five years was R. Durrett's development of methods for treating large classes of these models if one is willing to assume that the range of interaction is large or that the particles are moving at a fast rate. These assumptions are satisfied in many biological and physical systems and provide a reliable guide to the qualitative features of other systems, as well.

L. Billera, M. Kapranov, B. Sturmfels, and A. Zelevinsky did very significant work in the area of polytopes, generalized discriminants, and resultants. They established a conjecture of Baues arising in the geometry of loop spaces in homotopy theory. With V.A. Voevodsky, Kapranov settled a conjecture of Grothendieck in the homotopy theory of CW-complexes. In work with M. Falk of Northern Arizona University, Sturmfels solved a long-standing problem from the topological theory of complex hyperplane arrangements by constructing two arrangements with isomorphic matroids, but non-isomorphic fundamental groups.

M. Stillman, together with D. Bayer, did research and development on Macaulay which has become one of the major computer algebra systems for computations in algebraic geometry and commutative algebra. The system is in use world-wide. MSI-funded research ranged from the development of new, underlying theoretical mathematics to the actual implementation of the program.

R. Zippel, together with graduate student S. Rapkin and students of Prof. J. Lumley, developed automatic techniques to generate differential equations that model physical systems. Their work uses symbolic computation to generate the equations and ties together symbolic and numerical methods to make the equations easier to solve.

M. Sweedler, together with L. Robbiano and D. Shannon, developed the first systematically effective techniques for working with subalgebras and subfields.

Additionally, J. Marsden developed the energy momentum method and the block diagonalization technique in mechanics.

Appendices

	Appendix A:	Faculty and Visitor Research Reports
	Appendix B:	Postdoctoral Research
	Appendix C:	Graduate Student Research
	Appendix D:	MSI/US Army Collaborations
	Appendix E:	MSI Technical Reports

Faculty and Visitor Research Reports

James H. Bramble
Department of Mathematics, Cornell University

My research includes: multigrid methods including non-nested spaces, nonsymmetric and indefinite problems and higher order equations, multilevel preconditioners, domain decomposition, and parallel multilevel preconditioners. I am interested in implementation on computers with parallel architectures.

During the last five years I have collaboarted with J.E. Pasciak, A.H. Schatz, R.E. Ewing, J. Xu, V. Thomee, P. Sammon, Z. Leyk, D.Y. Kwak and R. Parashkevov. Leyk has been an MSI Postdoctoral Fellow for the last two years of this contract. Collaboration is currently with J.E. Pasciak, Brookhaven National Laboratory and M. Hanisch who was an MSI Postdoctoral Fellow during the last year of this contract.

During this five-year period three students received Ph.D. Degrees under my direction. They are J.Xu (MSI supported), Ping Lee and Mark Hanisch. During the same period twenty-one publications of mine have acknowledged MSI support.

Bruce R. Donald
Department of Computer Science, Cornell University

My research interests include robotics, computational geometry, spatial reasoning, and artificial intelligence. Robotics is the science which attempts to forge an intelligent connection between perception and action. In order to perceive and manipulate objects in the world, robots must be able to reason about *geometry and physics, and to plan and execute tasks in the presence of uncertainty in sensing, control,* and the geometry of the environment. I am particularly interested in the theory of manipulation and geometrical planning. Projects I am involved in now focus on motion planning, task-level planning, a theory of planning compliant motions and assemblies in the presence of geometric variation (uncertainty), a geometrical characterization of Error Detection and Recovery (EDR) for robotics, and the mathematical foundations of robotics.

To attain our goal of task-level planning, our research programme is a blend of theory, implementation, and experimentation. To test our theory of task-level assembly, we are working with graduate students Jim Jennings and Doug Campbell to implement compliant motion planning algorithms, and to build an experimental force-control system for the Cornell robot. This system represents one of the few attempts to verify the adequacy of an algorithmic theory of compliant motion planning by testing the plans on a force-controlled robot. We have also continued to refine and develop the theory. For example, with graduate student Amy Briggs we developed a new, nearly optimal algorithm for one-step compliant motion planning under uncertainty. The method is a quadratic factor faster than previous methods. With post-doctoral associate Dinesh Pai, we are developing a new, algorithmic theory of assembly for passively-compliant (flexible) objects. Whereas most approaches to robot motion planning deal only with rigid objects, our algorithms apply to devices such as snap-fasteners and ratchet-and-pawl mechanisms, which are slightly flexible and snap together when assembled.

Uncertainty in sensing, control, and modeling is perhaps the most fundamental problem in robotics today. To develop and explore new approaches to planning and sensing under uncertainty, we are building new experimental robotic devices. with graduate students Michael O'Donnell, Marius Moscovici, Jim Jennings, and Russell Brown, we are designing, constructing, controlling, and programming a mobile autonomous robotic platform to investigate planning, sensing, and execution in unstructured environments populated by humans and other robots .

Robots must be able to plan quickly and to execute their plans fast; to address this need, we have introduced powerful new mathematical methods that link complexity theory and control theory. From 1988-1990, in joint work with graduate student Pat Xavier and with John Canny of UC Berkeley and John Reif of Duke, we developed a new "high-level" algorithm for optimal kinodynamic planning. This algorithm may be applied in robotics to generate minimal time, collision-avoiding trajectories, that respect dynamics bounds. While exact solutions to this problem are unknown, we have discovered the first provably good approximation algorithm for optimal kinodynamic planning. Our bounds on solution accuracy and running time are the first that have been obtained for optimal kinodynamic planning, which has been an open problem in computational robotics for over ten years. Finally, the algorithm is so simple that it has already been implemented, and refinements and experimental analysis are underway.

Richard Durrett
Department of Mathematics, Cornell University

During the last year I continued my work on interacting particle systems. Most of my recent efforts go in two directions.

1. Cellular Automata. The Greenberg Hastings model is a simple system that models the behavior of an excitable medium. In this system each site can be in one of the states 1,..*k*, where 1 = excited, *k* =rested, and 2,...*k*-1 are recovery states. The rules of this model are simple: (i) if $\xi_n(x) < k$, then $\xi_{n+1}(x) = \xi_n(x)$, and (ii) if $\xi_n(x)$ and at least θ neighbors are excited then $\xi_{n+1}(x) = 1$, otherwise $\xi_{n+1}(x) = k$. However, depending upon the number of neighbors, ν, and the values of θ and *k*, a wide variety of behaviors can be observed. In **Multicolor particle systems with large threshold and range,** Durrett showed that if $\theta = (1-\varepsilon)\nu/2k$ with $\varepsilon>0$ and ν large, then the behavior observed is very boring: starting from a randomly chosen initial state each site is eventually period with period *k* and $\lim_{m\to\infty} \xi_{mk}(x)$ is very random. Although the last conclusion is not exciting, it is an important first step in exploring the "phase diagram" for these systems. Recent work with David Griffeath (a technical report is in preparation) concentrates on the more interesting "spiral phase" for this system. A survey of these results, **Some new games for your computer,** will appear as the cover story in the second issue of Nonlinear Science Today.

A second cellular automaton Durrett has investigated is the threshold voter automaton. In this system each site can be in state 0 or 1, which we think of representing two possible opinions of a voter at x. Again the rules are simple: if there are at least θ neighbors with a different opinion from the one at x, then $\xi_{n+1}(x) = 1-\xi_n(x)$, otherwise $\xi_{n+1}(x) = \xi_n(x)$. In **Fixation results for threshold voter automata,** joint work with MSI postdoc Jeff Steif, we investigated the case in which $\theta>$ one-half the number of neighbors. This regime may seem to be uninteresting, since in this case the system gets stuck: i.e., each voter changes his opinion only finitely many times. However, it turns out there is an interesting phase transition in the nature of the limiting picture that is related to large deviations.

2. Applications to biology. **Stochastic models of growth and competition,** written for the proceeding of the International Congress of Mathematicians held in Kyoto in August 1990, surveys recent work on interacting particle systems that model the spread of diseases and biological populations. A more recent addition to that body of knowledge is **Epidemics with recovery in d=2,** written with Claudia Neuhauser, who at the time was an MSI graduate fellow. The main result of that paper demonstrates that the standard model for an epidemic in a spatially distributed population has a nontrivial stationary distribution if the associated epidemic in which there is no regrowth of susceptibles is supercritical —i.e., has positive probability of not dying out when we start with a single infected individual in a population of otherwise healthy individuals. More recent results on this model show promise of shedding light on some old observations in epidemiology. Unless a population is large (250,000 or more) measles will die out from time to time, i.e., there will be times at which no one in the population is infected. If the population exceeds this critical size then there will be recurrent outbreaks but the number of infected individuals oscillates in time.

Interacting particle systems models are with increasing frequency being used by biologists. The summer school on "Patch Dynamics" held at Cornell and partially supported by MSI has a number of talks that featured this type of modeling. To treat applications, however, it is important to be able to obtain quantitative information about critical values. **Stochastic growth models: bounds on critical values** and the sequel written with Ted Cox, **Estimating the critical values of stochastic growth models**, deal with these important issues.

Eugene Dynkin
Department of Mathematics, Cornell University

I have been working on the relationship between Markov processses and random fields that arises in statistical physics and quantum field theory. Most recently, my work has been focused on measure-valued processes with the branching property. The name "superprocesses," suggested by me in 1987, is now widely used in the literature. Connections between superdiffusions and a class of nonlinear partial differential equations have been established making it possible to apply powerful analytic tools for investigating the path behavior of the process and providing a new approach to problems in the theory of nonlinear differential equations.

During my period of support seventeen of my publications have acknowledged MSI support.

Gregory Ezra
Department of Chemistry, Cornell University

Two of my students have been supported by MSI:
Craig Martens '86-'87
Thesis: "Nonlinear Dynamics of Large-amplitude Molecular Motions"
Laurence Fried '87-'88
Thesis: "Perturbation Theory Applied to Molecular Vibrations"
I also co-organized (with S. Wiggins) the MSI Workshop "Classical & Quantum Transport in Hamiltonian Systems" at Cornell in November 1989. Six publications acknowledged MSI/ARO support.

Walter T. Federer
Department of Plant Breeding and Biometry, Cornell University

Short courses were given in Kentucky, at Aberdeen Proving Ground, Maryland and Fort Belvoir, Virginia. One technical report on computer aids for constructing fractional replicates of large factorials is currently in the hands of my co-author, Charles McCulloch. I do not know when it will be completed. It is a paper for a special issue of a journal.

Consultations with Army research personnel at Fort Belvoir and at White Sands Proving Ground during 1991 have involved the construction and statistical analyses of fractional replicates. At White Sands, I recommended a 1/4 replicate of a 26 for a study on the factors velocity and size of tank, terrain, and 8 different sequences for firing missiles from the tank. We were to run the 16 combinations first and perhaps to run a second 1/4 replicate after studying the results of the first 16 combinations. It was costly and time consuming to run each combination. Hence, as few combinations as possible were desired. The experiment was never conducted as it was a casualty of the Gulf War.

One book, **"Statistics and Society. Data Collection and Interpretation,"** was published in May, 1991. A second book, **"Statistical Design and Analysis for Intercropping Experiments,"** is nearing completion. It deals with statistical design and analysis of mixtures of several components (systems) and involves quite different methods than commonly used for comparative experiments.

Boris L. Granovsky
Department of Mathematics, Technion, Isreal
Research Coordinator: Rick Durrett

It is proven that ε>m condition implies concavity of the mean coverage function on a finite lattice in the case of an arbitrary spin system. This result provides a sufficient condition of concavity of a mean coverage density function on an infinite homogeneous lattice. Following a suggestion by R. Durrett, a study of concavity in the case of an infinite mean field system was originated.

Andreas Greven
University of Gottingen, Germany
Research Coordinator: Richard Durrett

My area of research is probability, to include: System of interacting diffusions, Markov Processes, Hierarchical systems, and Fleming-Viot Models.

New research projects begun at MSI include:
1. Scaling limits of interacting diffusions
2. Large systems of interacting Fleming-Viot Models
This is research jointly with Ted Cox (Syracuse) and D. Dawson (Ottawa) and has been greatly inspired by many discussions with R. Durrett.

I also worked on the completion of the following projects:
1. Coupling of continuous time Markov processes (with M. Cranston, Uni. of Rochester)
2. Low dimensional branching Brownian Motion (with T. Cox, Syracuse and M. Bramson, Univ. of Wisconsin)

Ali Hadi
Department of Economic and Social Statistics, Cornell University

My MSI activities from 1985-1991 have been concentrated on giving numerous tutorials on the following three subjects: Sensitivity Analysis in Linear Regression, Applied Regression Methods, and Graphical Methods for Data Analysis.

Also, MSI support has been acknowledged in the following publications:

Diagnosing Near Collinearities in Least Squares Regression, with P.F. Velleman.

A Discussion of Collinearity and Least Squares Regression, by G.W. Stewart, Statistical Science Vol. 2, No. 1, 93-98, 1987

The Prediction Matrix: Its Properties and Role in Data Analysis, Proceedings of the Business and Economic Statistics Section, Americal Statistical Association, 631-636, 1986.

Timothy J. Healey
Department of Theoretical and Applied Mechanics, Cornell University

During the period 1988-1991, I received MSI support for my research on the use of symmetry and group-theoretic ideas in the analysis of nonlinear differential equations, particularly global bifurcation and continuation problems, with applications to mechanics. Our results, represented by the papers shown below, include (i) efficient numerical methods, [1] & [5], (ii) uncovering new solutions and new phenomena in mechanics, [2],[3],[4],[5],[7],[11],[13],[14], (iii) the establishment of nodal properties of solutions in

global bifurcation problems, [6],[8],[9],[12]. Our most dramatic results are reported in [6] & [12], where we present the first generalizations of classical results of Crandall and Rabinowitz (for ordinary differential equations) to elliptic partial differential equations.

During the 1989-90 academic year, my graduate student Jay Treacy received MSI support.

[1] Numerical Bifurcation with Symmetry: Diagnosis & Computation of Singular Points, in Proceeding of the International Conference on Bifurcation Theory and Its Numerical Analysis, eds., Li Kaitai, J. Marsden, M. Golubitsky & G. Iooss, Xian Jiaotong University Press (1989) 218-227.

[2] Steady Axial Motions of Strings (with J. Papadopoulos), J. Appl. Mech. 57 (1990) 785-787.

[3] Large Rotating States of a Conducting Elastic Wire in a Magnetic Field: Subtle Symmetry and Multiparameter bifurcation, J. Elasticity 24 (1990) 211-228.

[4] Stability and Bifurcation of Rotating Nonlinearly Elastic Loops, Quart. Appl. M Math. XLVII (1990) 679-698.

[5] Exact Block Diagonalization of Large Eigenvalue Problems for Structures with Symmetry (with J. Treacy), Inter. J. Mech. Engrg. 31 (1991) 265-285.

[6] Symmetry and Nodal Properties in Global Bifurcation Analysis of Quasi-Linear Elliptic Equations (with H. Keilhofer), Arch. Rat. Mech. Anal. 113 (1991) 299-311.

[7] Bifurcation to Pear-Shaped Equilibria of Pressurized Spherical Membranes (with Y.-C. Chen), Int. J. Nonl. Mech. 26 (1991) 279-291.

[8] Positivity of Global Branches of Fully Nonlinear Elliptic Boundary Value Problems (with H. Kielhofer), Proc. AMS (1991, in Press).

[9] Hidden Symmetry of Fully Nonlinear Boundary Conditions in Elliptic Equations: Global Bifurcation and Nodal Structure (with H. Kielhofer), Results in Math. (1991, in press).

[10] Symmetry and Nodal Properties in Systems of Nonlinear Sturm-Liouville Eigenvalue Problems, submitted to Nonl. Anal.: Theory, Meth. Appl. (1990) (Under revision).

[11] Large Rotation Oscillations of Nonlinearly Elastic Rods: Spatio-Temporal Symmetry-Breaking Bifurcation, SIAM J. Appl. Math (1991, in press).

[12] Preservation of Nodal Structure on Global Bifurcating Solution Branches of Elliptic Equations with Symmetry (with H. Kielhofer), submitted to J. Diff. Eq. (1991).

[13] Local Solutions of the Traction Problem for Elastic Aeolotropic Bodies of Revolution: Symmetry Reduction and Continuation, to appear in Proc. ASME Winter Annual Meeting, Atlanta, Dec. 1991.

[14] Hidden Symmetry and Global Continuation for a Class of Mixed Boundary Value Problems in Nonlinear Elastostatics (with H. Simpson)

[15] Computation of Multiple Symmetry Breaking Bifurcation Points of conservative Systems.

[16] Stability of Large-Amplitude Rotating States of Nonlinearly Elastic Strings (with A. Block).

[17] Quasi-Periodic Motions Near Relative Equilibria of Elastic Structures with Symmetry (with T. Whalen).

David C. Heath
School of Operations Research and Industrial Engineering, Cornell Univrsity

During the period from 1986 through 1991, I organized two MSI workshops (on Stochastic Control and Finance), and received support in the first year. My relationship with MSI continued during the grant as a consultant.

Philip J. Holmes
Department of Theoretical and Applied Mechanics, Cornell University

During this period I acted as Coordinator for Applied Analysis for all but the academic year 1988-89, when I was a Fairchild Scholar at the California Institute of Technology. In Fall 1989 I shared the activity with Jerrold Marsden. Reports on the activities, workshops and research projects of the many students, postdoctoral fellows and visiting faculty supported by MSI can be found elsewhere, along with lists of MSI reports and other publications arising from their work. Many of the MSI visitors and postdocs also conducted seminars or offered courses in their research areas. In what follows I summarise only those parts of my own research activities supported by MSI or carried out with MSI personnel. I first list those in the latter category with whom I have interacted.

Visiting Faculty: R.D. James, J.M. Ball (1988); M. Field, D.D. Holm, P. Krishnaprasad, J. Scheurle, C.A. Stuart (1989-90).

Postdoctoral Fellows: D. Armbruster (1986-88), A. Mielke (1986-87, 89), A. Bloch (1987-89), D. Lewis (1987-89), E. Titi (1988-89, 90-91), J. Elezgaray (1990-91).

Graduate Fellows Supervised: T. Kiemel (1988-89), P. Swart (1990-91).

I now describe the research projects: I give references only to Journal publications and, where relevant, MSI reports. During the five year period I also gave invited lectures at 36 conferences, including a plenary address at the XI US Congress on Applied Mechanics and a sectional address at the International Congress of Mathematicians. Many of these lectures have appeared in volumes of Proceedings or led to extensive reviews.

1. Knots and Orbit Genealogies. For a number of years I have been using invariants of knot theory to distinguish and follow branches of periodic orbits in parameterised families of three dimensional flows. This led to a series of six papers, one of which was written with MSI support (Report 87-39).

2. Neuronal Oscillations. In 1988-89 my student Tim Keimel was an MSI fellow. He completed his PhD thesis "Three Problems from the Mathematics of Neuronal Oscillators" in 1990 and currently holds an NSF postdoctoral fellowship at NIH.

3. Homoclinic Orbits. Dieter Armbruster (MSI postdoc), John Guckenheimer and I discovered structually stable heteroclinic cycles in certian symmetric dynamical systems, provided the first fairly complete analyses of them, and showed that they are fundamental in understanding intermittent behavior in fluid flows. This work is currently being extended in several directions.

Alex Mielke (MSI postdoc) and I used perturbation from an integrable limit and Kirchhoff's "dynamical analogy" to study spatially complex equilibrium states of rods and then, with my student Oliver O'Reilly, analysed homoclinic bifurcations in two degree of freedom Hamiltonian model for the non-planar oscillations of a taut string (MSI Tech. Rep. 90-85).

C.A. Stuart (MSI visitor) and I developed topological ideas to prove the existence of "large amplitude" homoclinic orbits in ODEs which are autonomous for large values of the independent variable, such as arise as boundary value problems in EM waveguide theory (MSI Tech. Rep. 90-64).

J.E. Marsden, J. Scheurle (MSI visitor) and I worked on exponentially small splitting of seperatrices in rapidly forced oscillators. Such "beyond all orders" phenomena are analytically challenging and important in several fields, such as KAM theory and crystal growth.

4. Turbulence. My joint work with J.L. Lumley, S. Leibovich and J. Guckenheimer on low dimensional models for the dynamics of coherent structures in boundary layers has been supported primarily by AFOSR and ONR, but three MSI postdoctoral fellows, Armbruster, Bloch, and Titi, have made essential contributions and provided a valuable intellectual resource for both faculty and graduate students.

5. Nonlinear Stability of Rotating Systems. Inspired by the semester organised by Marsden on Hamiltonian systems and stability in 1989, my student Brett Zombro and I have been using the "energy momentum" method to study the stability of discrete and continuum systems. We focus especially on situations where the method fails (the amended potential is indefinite with even index) and we have found explicit criteria for linear stability/instability in these cases.

6. The Dynamics of Phase Transformation. Perhaps the most striking work, and that which has occupied much of my energy since 1989, is an attempt to understand the role of dynamical effects in the creation of "fine structure" (eg, twinning) in continuum models of material phase transformations. This work originated in MSI sponsored visits by R.D. James and J.M. Ball and much of it was done with my student Pieter Swart, who was an MSI fellow in 1990-91 and has now graduated and taken up a postdoctoral fellowship at Carnegie-Mellon University. We obtained a reasonably complete understanding of some one-dimensional models (MSI Tech. Rep. 90-67) and Swart developed numerical methods, including a ground-breaking wavelet code, to explore a two-dimensional anti-plane shear problem. A video of simulations produced at the Cornell National Supercomputer Facility has generated enormous interest and we have made several theoretical inroads to the problem. We expect that Swart's thesis: "The Dynamical Creation of Microstructure in Material Phase Transformations" (1991), will lead to several publications.

Chung-Yuen Hui
Department of Theoretical and Applied Mechanics, Cornell University

In collaboration with Professor Bassani (MSI workshop participant) and his group at the University of Pennsylvania, we have carried out a detailed study of the asymptotic stress fields near the tip of a growing plane strain mode 1 crack under small scale yielding conditions [1]. The non-linear material behaviour is assumed to be confined inside a cohesive zone directly ahead of the growing crack tip. We have demonstrated a general method to analyse the singularity of the stress field. This method is applied to the special case of a power-law material in which the rate of opening displacement is proportional to the power of tensile stress. Numerical computation is used to verify our asymptotic analysis for this special case. The relationship between the crack growth rate and the applied stress intensity factor is determined by imposing a critical crack opening displacement criterion.

In collaboration with Professor Sam Sham at Rensselaer Polytechnic Institute (RPI), (former MSI visitor) we have carried out an aymptotic analysis of the deformation field near the tip of a steadily growing crack in a creep damaged material under small damage conditions [2]. For the case of stationary cracks, it has been shown that a singular stress field does not exist for time greater than zero. However, our analysis shows that singular crack tip fields are possible if the crack growth rate is sufficiently fast. Our asymptotic analysis was confirmed recently by our finite element calculation.

In collaboration with Professor K.C. Wu (a former MSI visitor), the growth history of a macroscopic crack at high temperature is studied using a crack growth criterion based on void growth and coalescence [3]. Two models of crack growth are considered: a discrete model in which the crack advances by discrete jumps and a continuous model in which the crack advances due to damage accumulated ahead of the crack tip. Our results show that, irrespective of the void growth mechanisms, the continuous and discrete models give practically the same results. The effect of void nucleation is included in the analysis by assuming a critical void nucleation stress. For the case of continuous crack growth, an exact solution for the entire growth history is obtained as a funciton of the path independent integral C^* for a wide variety of crack growth mechanisms. Both discrete and continuous models show that crack growth exhibits

"stop" and "go" episodes is shown to decrease exponentially to zero with a characteristic distance of R, where R is the nucleation distance. The steady state crack growth rate is found to be approximately proportional to C*, independent of the void growth mechanisms. The presence of a breakpoint commonly observed in experiments can be explained by our analysis.

In coorporation with Dr. Gan Bao, a former MSI visitor, we have completed a study on the effect of interface debonding on the ductile particle toughening of ceramic materials [4]. To utilize the ductility of the particles in the toughening process, it is necessary to have a satisfactory bonding between the matrix and the particles. However, partial debonding of the matrix-particle interface can occur due to stress concentration near the crack tip. Debonding relaxes the lateral constraint which increases the plastic stretching of the particles. Most previous estimates of toughening have been based on the assumption of perfect bonding. We have derived an approximate analytical expression of the plastic stretching of a partially debonded ductile particle in the bridging zone. An interface model based on the debonding-stretching model is then used to determine the size and the opening displacement in the bridging zone for a plane strain mode 1 crack loaded under small scale bridging conditions. The length and the opening displacement of the bridging zone is determined numerically as a function of the applied stress intensity factor by solving a non-linear singular integral equation. The theoretical prediction of the fracture toughness based on the debonding-stretching model is closer to that measured by experiment when compared to models based on stretching alone.

The stress and deformation field near a broken fiber in a micro-composite is studied using different interface models. These interface models describe the physical mechanism of imperfect bonding between the fiber and the matrix. In collaboration with Dr. E.C. Chen, a former MSI post-doctoral fellow, we studied the deformation field at the matrix-fiber interface of a broken fiber [5]. The interface is modeled as either linearly elastic or elastic-perfectly plastic. An exact solution is obtained in the first case. In the second case we also investigated the possibility of mode 2 crack growth along the interface. Our numerical solution shows that interface crack growth becomes unstable when the applied loading exceeds a critical amount. This corresponds physically to fiber pull-out.

In collaboration with Professor D. Lagoudas, of RPI, a former MSI Postdoctoral Fellow, we have completed a finite element study of the effect of frictional interface on the load diffusion from a broken fiber to the surrounding matrix material [6]. The extent of the debonding zone near the fiber break is determined using a finite element method. An analytic solution, based on the shear-lag approximation, is carried out to obtain a closed form solution of the fiber load diffusion problem. Our numerical results show that the shear-lag approximation is valid for small frictional coefficients or large applied strains that lead to relatively large slip zone lengths.

In collaboration with Professor D. Lagoudas (former MSI postdoctoral fellow) and Professor L. Phoenix (MSI member), the overload profile of the neighboring fibers due to broken fibers is investigated using a shear-lag model which is applied to a monolayer, unidirectional, fiber reinforced composite loaded in tension[7]. The monolayer contains an infinite number of parallel fibers, with an arbitary number of them broken simultaneously. The matrix is assumed to be viscoelastic. The time evolution of the overstress profile in the fibers and the matrix is determined and the time dependence of the effective load transfer length is calculated. Exact closed form solutions as well as approximate evaluations of the above quantities are given for a power law creep compliance model, suitable for most epoxy materials.

Instead of modeling the matrix as linearly visco-elastic, we examine the possibility of using non-linear creep models whose memory is also dependent on the stress level for the matrix material in the problem described above . In collaboration with Professor L. Phoenix and his student D. Mason we have shown that selfsimilar solutions exist under initial and boundary conditions which simulate a broken fiber embedded midway between other intact fibers [8]. Numerically solution of these self-similar solutions are used to determine the matrix shear stress, fiber strains, and the overload regions in the neighborhood of a single fiber failure for the quasi-static case. Finally, and exact, closed form solution is obtained for the special case of the "single fiber problem" without matrix memory.

In collaboration with Professor D. Lagoudas and my student Y.C. Wang (graduate student,. supported by MSI during 89-90) we have completed a detailed study of the effect of crack tip blunting when a crack is impinged upon a bimaterial, frictional interace [9,10]. The interface is modeled as a continuous distribution of edge dislocations. The jump discontinuites associated with these dislocations are related to the history of traction on the interface thorugh Coulomb friction. It is found that the stress field near the crack tip is finite and no opening zone developed for small friction coefficient. For sufficiently high frictional coefficient, the slip zone is preceded by an opening zone or a mode 1 interface crack.

In collaboraton with Professor D. Lagoudas of RPI, we studied the effect of interface constitutive model on the mechanical stability of the interface [11]. We demonstrated that rate independent softening interface models could lead to non-unique solutions in typical boundary value problems. This non-uniqueness corresponds to instabilities on the interfces which manifest as crack initiation and growth. These general results are applied to the problem of crazing in polymer glasses and the condition for instability is derived for a straight infinite interface under homogenous loading conditions.

Publications supported by MSI:

1. L.O. Fager, C.Y. Hui, D.B. Xu and J. Bassani, "Aspects of Cohesive Zone Models and Crack growth in Rate Dependent Materials", accepted for publication by Intl. J. Fracture, Nov. (1989).

2. C.Y. Hui an S. Sham, " The Asymptotic Stress and Strain Fields near the Tip of a Growing Crack under Creep Damage Conditoins" in preparation.

3. C.Y. Hui and K.C. Wu , " Growth of Macroscopic Cracks by Void Coalescence under Extensively Creeping Conditions", in: eds. A Saxena, J.D. Landes, J. Bassani, Non-Linear Fracture Mechanics: Vol. 1, Time Dependent Fracture, STM STP 995, (1988).

4. Gang Bao and C.Y. Hui, "Effects of Interface Debonding on the Toughness of Ductile-Particle Reinforced Ceramics", in print, Intl. J. Solids Sturctures, (1989).

5. E.C. Chen and C.Y. Hui, "Analysis of a Broken Fiber in a Composite with Imperfect Bonding", accepted by Mechanics of Materials, April, (1990).

6. B. Aksel, D. Lagoudas and C.Y. Hui, "Effects of a Frictional Interface on the Load Diffusion from a Broken Filament Embedded in an Elastic Medium", accepted for publication by Intl. J. of Solids and Structures, (1989)

7. D. Lagoudas, C.Y. Hui and L. Phoenix, "Time Evolution of Overstress Profiles near Broken Fibers in a Composite with a Viscoelastic Matrix", Int. J. Solids Sturctures, VO1.25, No. 1, (1989).

8. D. Mason, L. Phoenix and C.Y. Hui, "Time Dependence of the Deformation fields around Fiber Breaks in a Composite with a Power-law Creeping Matrix", In preparation. (1990)

9. C.Y. Hui and D. Lagoudas, "Stress Fields of Interface Dislocations", JAM, Transaction of the ASME, Vol. 57/1, March (1990).

10. Y.C. Wang , C.Y. Hui, D. Lagoudas and J. Papadopoulos, "Small Scale Crack Blunting at a Bimaterial Interface with Coulomb Friction", Submitted to Intl. J. Fracture, (1990).

11. C.Y. Hui, D. Lagoudas and A. Ruina, "Constitutive Models for Crazes and their Effects on Crack Growth in Glassy Polymers", in: eds. V.K. Stokes and D. Krajcinovic, Constitutive Modelling for Nontraditional Materials, AMD-Vol.85, ASME, (1987).

Jiunn T. Hwang
Department of Mathematics, Cornell University

Financial support from MSI of my project was for Richard Liu and a workshop.
Richard Liu has worked out many research papers. The workshop held in the summer of 1991 created a stimulating environment. The invited speakers included J.O. Berger, Chris Robert, Bill Strawderman, and Roger Berger. Stimulating conversation took place which will have important influence on the work in the area of conditional inference.

James T. Jenkins
Department of Theoretical and Applied Mechanics, Cornell University
Ying Zhang
Mathematical Sciences Institute
Paul Dawson and Vincent C. Prantil
Department of Mechanical and Aerospace Engineering, Cornell University

Significant changes in the mechanical state of polycrystalline metals accompany the large deformations associated with forming operations. Crystallographic texture is one important source of the developing anistropy in the flow stress and the macroscopic response observed in these materials. Polycrystalline models provide descriptions of macroscopic material behavior by averaging the response of an aggregate of crystals underlying a material point. For such averaged quantities to be representative at the continuum level, it is necessary to average over several hundred single crystals. We have developed a means of obtaining a macroscopic constitutive model rich in microstructural detail, without the necessity of retaining large amounts of information at the level of the individual grains.

In order to concentrate on the elements necessary to construct a continuum description of anisotropic stiffness, the geometric hardening of an idealized planar assembly of two-dimensional grains was first examined. A Taylor assumption was used to link the macroscopic and microscopic length scales. Consequently, the macroscopic deformation rate is imposed on each crystal. Constitutive relations describing viscous slip at the grain level relate the slip system shearing rate to the resolved shear stress on the slip planes. After solving the microscopic response at the slip system level, an average stress for the aggregate was obtained using an orientation average. Further, equations of evolution for the grain orientation were derived and expressed in terms of the macroscopic deformation rate and a single microstructural parameter. An analytical expression for the plastic spin and other features of the developing anisotropy of the aggregate have been determined in terms of this parameter.

The anisotropy of the aggregate is represented by a continuous orientational distribution function. When the equations of evolution for the grain orientation are known, the distribution function can be expanded as a Fourier series of spherical harmonics. The set of even order tensors corresponding to moments of the distribution have been identified. Also, equations of evolution for the moment tensors have been derived. Lower moments provide descriptions of the distribution function that, near the onset of texturing, compare well with discrete polycrystalline simulations and analytic solutions in uniaxial tension and simple shear. Such comparisons identify quantitative levels of induced anisotropy beyond which higher moments are necessary to capture the material response.

The corresponding activity has been carried out for three dimensional polycrystals, with particular emphasis on face-centered cubic crystals.

Recent publications that acknowledge MSI support:

Jenkins, J.T. and Askari, E., 1991 Boundary conditions for rapid granular flows: phase interfaces. Journal of Fluid Mechanics 223, 497-508.

Jenkins, J. T., 1991 Boundary conditions for rapid granular flows: flat,frictional walls. Journal of Applied Mechanics (in press).

Jenkins, J. T., 1991 Anisotropic elasticity for random arrays of identical spheres. pages 368-377 in Modern Theory of Anisotropic Elasticity and Applications, J.J. Wu, T.C.T. Ting, and D.M. Barnett, editors, SIAM: Philadelphia.

Zhang, Y. and Jenkins, J.T. The evolution of the anisotropy of a polycrystalline aggregate. Journal of the Mechanics and Physics of Solids (under review).

Peter J. Kahn
Department of Mathematics, Cornell University

My research interests include: problems in algebraic and differential topology and geometry that arise in the mathematical foundations of computer modeling, simulation, and robotics.

(1) *Constructive differential topology.* Many of the basic objects and techniques in the mathematical foundations of modeling and robotics involve differential topology. To give two non-trivial examples: (a) The doctoral thesis of Dinesh Pai analyzes the singularity structure of simple robot arms, using the singularity theory of Whitney, Boardaman, et al. (b) The award-winning doctoral thesis of John Canny uses an elaborate version of Morse theory applied to stratified spaces to obtain a new and better algorithm for solving the Piano Movers Problem. Other even more obvious uses of differential topology in connection with computation occur in the qualitative analysis of dynamical systems. Since differential topology and geometry are part of classical mathematics, the question arises as to which concepts and parts of these subjects are amenable to or useful for computational techniques and analysis. Or, starting at the other end, to what extent can differential topology and geometry be made constructive? Professor Kahn and Dr. Catherine Wagner have been studying this question and have come up with several partial answers.

Virtually all of the local theory of basic differential topology has a constructive version. The deepest result in this part of the theory, a constructive proof of Sard's Theorem, is due to Y-K Chan. In principle, this provides an algorithm for finding regular values of maps. Kahn and Wagner are presently extracting such an algorithm from Chan's proof and doing a complexity analysis, but almost certainly, improvements will be needed before this becomes of practical interest. The basic question in the global theory is how to give a useful definition of a differentiable manifold. The classical notions of compactness and paracompactness are not constructive, and this makes problematic the construction of partitions of unity. This in turn creates problems for most of the basic global constructions. Kahn and Wagner have a candidate for a good definition, in terms of notions of a "well-placed" open cover (replacing the more general notion of open cover) which does allow the construction of a reasonably rich family of smooth partitions of unity. Many global constructions then become constructive, virtually automatically. It remains to test the definition against all the main results and examples. Further problems include: (a) Extensions to differential geometry, (b) Interactions with the global theory of dynamical systems, and (c) Producing specific algorithms.

(2) *Categorical homology and applied geometry.* Numerous questions and techniques in applied geometry can best be expressed in terms of a type of sheaf-theoretic homology (or "homology of a category with coefficients in a functor"). Kahn has been working out the properties of this theory together with L. Billera, and they have been attempting to apply it to some outstanding problems in combinatorics. Although this latter effort has yielded new insights, it has not yet produced substantial new results. Kahn and Billera are preparing a survey paper on this.

Simon A. Levin
Department of Ecology and Systematics, Cornell University

Work supported by MSI has covered a variety of projects involving the application of mathematics to biological problems. Eleven publications have resulted, including two Ph.D. theses. In the past year, three new publication have resulted dealing with the use of stochastic models to simulate the dynamics of plant populations in heterogeneous environments. The objective of this work has been to develop methods to relate patterns observed at broad spatial scales, through techniques such as remote sensing, to processes operating at the level of individuals. Detection of patterns of self-similarity in spatial data has motivated the search for the factors that determine correlations; interacting particle models and extensions provide a logical framework.

Work accepted for publication in the past year develops a comparison of methods for the analysis of spatial data; models for pattern formation in a serpentine grassland; and analysis of the evolutionary stability of plant communities. Additional support was provided for co-sponsorship of a month-long workshop on patch dynamics in marine and terrestiral systems.

As a result of this research, nine publications have acknowledged MSI support.

Philip L.F. Liu
Department of Civil and Environmental Engineering, Cornell Univresity

Summary: Using the Hamiltonian theory a new set of Boussineq equations has been derived. These equations cover a wider range of frequencies. Therefore, these equations are stable subject to numerically generated short waves. Currently, we are developing numerical schemes to solve these Boussinesq-type equations.

Laboratory experiments of wave-current interactions were carried out in the Waterways Experiment Station. Mr. Mike Briggs, research engineer at the Coastal Engineering Research Center, participated in the experimental program. In these experiments, on-offshore currents were generated on a sloping beach. Obliquely and normal incident waves propagate from offshore towards shoreline, interacting with currents and beach bathymetry. Presently, we are analyzing the data. The theory developed by the project will be verified and compared with data.

Subrata Mukherjee
Department of Theoretical and Applied Mathematics, Cornell University

The Mathematical Sciences Institute (MSI) has partially supported my research in the area of determination of design sensitivity coefficients (DSCs) for nonlinear problems in solid mechanics. DSCs are rates of change of response variables such as stresses or displacements, in a loaded structure, with respect to design variables. The design variables in this work are shape parameters that control the initial shape of part or all of a body. Calculation of DSCs is important in many applications such as shape optimization, judging the robustness of a design, solution of inverse problems, and reliability analyses.

Most of the published work in this area is concerned with determination of DSCs for linear elasticity. The research here, however, has been focused on DSCs for nonlinear problems in solid mechanics. In particular, two classes of problems have been considered. The first is elasto-plastic problems with small strains and rotations. These are problems that are materially nonlinear, but geometrically linear. The second class of problems is both geometrically and materially nonlinear, in the sense that plastic deformations as well as large strains and rotations are included in the analysis. Both classes of problems have been solved by using the direct differentiation approach (DAA) of the governing boundary element method (BEM) equations of the problem. Two papers have been published, based on this work, and are listed below.

During the period, May 1990-April 1991, I consulted with Dr. Peter Chen of Watervliet Arsenal in the area of the above research and the general area of plasticity. We had several meetings in which we discussed problems of mutual interest.

1. S. Mukherjee and A. Chandra, A boundary element formulation for design sensitivities in materially nonlinear problems, Acta Mechanica, 78, 243-253 (1989).

2. S. Mukherjee and A. Chandra, A boundary element formulation for design sensitivities in problems involving both geometric and material nonlinearities, Mathematical and Computer Modelling, 15, 245-255 (1991).

Vicki Bergmann, a graduate student in Theoretical and Applied Mechanics during 1984-1989, received a MSI Fellowship for two years. She completed her Ph.D. in 1989.

Anil Nerode
Department of Mathematics, Cornell University
Director, Mathematical Sciences Institute

The five year program for new starts which was the Director's program, and constituted 20% of the research budget, had many positive results for the MSI Research Program for Cornell Applied Mathematics, and for ARO research thrusts.

Foremost achievements were the formation of a very strong stochastic analysis program (not part of the original MSI configuration, which was limited to applied probability and statistics by virtue of the original RFP), which has been continued as the Center for Stochastic Analysis, and the formation of what is arguably the strongest group in the world in computational algebra and logic, (also not foreseen in the original MSI configuration), which has been continued as the Center for Symbolic Methods in Algorithmic Mathematics. This shows the virtues of discretionary funding in meeting the demands of the future as the scientific world changes around us.

Next, the Director's program allowed the formation of especially strong concentrations in specific areas, such as the Dynamical Systems year of Jerry Marsden, and permitted MSI to invite extraordinarily strong mathematicians to share their wisdom with us as available.

Last, the Director's program allowed the formation of world class workshops in newly emerging areas that fall between the cracks of conventional centers, such as the workshops in Feasible Mathematics, and the workshops in Hybrid Systems. The latter effort has led to a major commitment by DARPA to MSI and collaborators in domain specific software for development of digital control programs for large interacting reactive systems with many inputs and effectors.

Shmuel Onn
School of Operations Research and Industrial Engineering, Cornell University

My research in the academic year 1990-91 was primarily concerned with a broad class of matriods and convex polytopes arising from finite permutation groups. This research is summarized in MSI technical report #91-12 (see[1]), and the abstract is the following.

Each group G of permutation matrices gives rise to *permutation polytope* $P(G) = conv\,(G)$ contained in $\mathbf{R}^{d\times d}$, and, for any $x \in \mathbf{R}^d$, an *orbit polytope* $P(G,x) = conv\,(G{\cdot}x)$. A special subclass is formed by the Young per-

mutation polytopes, which correspond bijectively to partitions $\lambda=([_1,\ldots,\lambda_k) \perp n$, $n \in$ N. Young polytopes, such as the traveling salesman polytope, arise naturally inpolyhedral combinatorics, and many algorithmic combinatorial problems, such as deciding hypergraph isomorphism, reduce to optimizing linear functionals over such polytopes.

I continued my study, initiated in [2], of the Radon and Tverberg functions of the integer lattice (see also my semiannual report to MSI), and a joint study wiht Professor L.E. Trotter of Cornell, on separation properties and polarity in vector spaces over arbitrary ordered fields [3].

[1] S. Onn, On the cominatoriics of Permutatio Polytopes, MSI tech. rept. 91-12, submitted to J. Combin. Theory Ser. A.

[2] S. Onn, On the Geometry and Computational complexity of Radon Partitions in the Integer Lattice, SIAM J. Discr. Math. (4) 1991, to appear.

[3] S. Onn and L.E. Trotter, on Separation in Vector Spaces Over Ordered Fields, in preparation.

S. Leigh Phoenix
Department of Theoretical and Applied Mechanics, Cornell University

Our work has focused on probability models of material breakdown wherein the material is modeled as a network or lattice of elements, each of which may be present or absent with certain probability, or have randomly distributed strength, or fail in time according to a distribution which is a prescribed functional of the load history. A key feature has been stress redistribution from failed to surviving elements, thus enhancing their failure rates. Models of this sort, which have a close connection to the theory of percolation and particle systems, have been used to explain the breakdown and size effects in strength of diverse structures such as fibrous composites, dielectrics, superconducting random networks and random fuse networks.

Our work earlier in the period focused on localized stress redistribution rules where we derived and published (with C.C. Kuo) a key recursion and limit theorem in terms of a characteristic distribution function for the lifetime distribution of a fibrous network. To answer key questions on convergence, size scaling and lower tail properties of the characteristic distribution function, we studied (with D.G. Harlow) a simple 0-1 model for strength for which we could derive exact and asymptotic results. This work was extended under a more diffuse load-sharing rule (with R.L. Smith) which revealed that certain features of the size scaling and distributional form depended in a non-trivial way on the exact details of stress redistribution near the tip of a critical cluster. On the whole, these results have revealed a richness of size scaling laws and distributional forms for strength.

In the most recent period we have considered (with W.I. Newman) the failure properties of hierarchically organized bundles under equal load-sharing. This problem can be treated exactly by renormalization methods and we considered the failure properties both as a function of time and of the applied load. The hazard rate for an element depends on load as a scale-free power law or as an exponential containing an intrinsic "temperature" scale. The scale-free power-law case is amenable to simple but exact renormalizaiton via a contraction map, producing a critical point in time in a broad array of problems. This contrasts with the static analogues which show a continuing decay in strength with increasing material volume with no emerging critical point.

Other work has been carried out (with C.-Y. Hui and D.C. Lagoudas) on load tranfer among elastic fibers in a power-law, viscoelastic matrix. The results have provided load redistribution constants and length scales as a function of time for use in the network models above.

Daniel Ralph
Department of Computer Science, Cornell University

An interest in nondifferentiable systems has led to analysis of methods for solving piecewise smooth equations that specify, for example, first-order optimality conditions for constrained optimization problems. Recent progress includes a general Newton's method for possibly nonsmooth systems with many solutions, such as feasibility problems in mathematical programming. This was presented at the May, 1991 joint national meeting of the Operations Research Society of America and the Institute of Management Sciences (Nashville,. TN). Also in progress is work on Gauss-Newton ideas for such problems, which is being jointly carried out with Professor Michael Ferris of the University of Wisconsin-Madison. A presentation on this was given in August, 1991 at the 14th International Symposium on Mathematical Programming (Amsterdam, The Netherlands). This work also has applications in two level optimization, such as minimizing a function some of whose variables are required to optimize a minimization subproblem, while the remaining variables determine the data of the subproblem.

Discrete time optimal control problems are also of special interest. Applications at Cornell include ground water detoxification, studied by Professor Chris Shoemaker and her colleagues (Civil and Environmental Engr.), and the aircraft trajectory problems of Professor Mark Psiaki (Mechanical and Aerospace Engr.). These provide large-scale structured problems for which parallel algorithms and computation are of practical importance. My research is in the preliminary stage.

1. D. Ralph, Regularity, and Newton's Method for Nonsmooth Functions Without Invertibility, manuscript in progress.
2. M.C. Ferris and D., Ralph, A Gauss-Newton Approach to the Normal Formulation of Nonlinear Complementarity Problems, manuscript in progress.

Sidney Resnick
School of Operations Research and Industrial Engineering, Cornell University

Choice Theory: With Rishin Roy, a PhD student from the Johnson School of Management, several models of consumer choice have been investigated which have close ties with extreme value theory. Imagine a consumer who must choose between d options at time t. Choice of option is based on utility maximization: Item i is chosen at time t if the utility of this item is larger than the utilities of the other items. This dynamic choice problem is made tractable by assuming that the stochastic process of utilities is represented by a d-dimensiona extremal Y(t). This assumption leads to results which give good agreement with those obtained in the marketing and economics literature by ad hoc means. The process of crucial interest is the leader process J(t) . J indicates which component is largest. It turns out that the process is Markov and, in usual cases, $\{J(t)\}$ is Markov with state space $\{1,...,d\}$. In fact usually the time change process $\{J(e^t)\}$ is homogeneous and simple expressions can be given for the stationary transition probabilities. There is hope that the simplicity of these expressions will lend themselves to statistical estimation so that model fitting to data can be attempted. Some useful independence properties of the processes have also been discovered which may help with model fitting.

A second class of models involve models for continuous choice where the set of alternatives is not finite. Examples concern choosing the time to leave, choosing a time slot for a television commercial, choosing the location of a new business etc. If we assume that the process Y is a max-stable process then we are able to calculate explicitly the hitting and inclusion functionals of the random set M, thus characterizing the distribution of this set of points of maximum utility. How to choose the spectral functions of the max-stable process is crucial but puzzling and we are starting to think about this problem now.

Random sets: In addition to the material on random sets pertinent to choice models , Keizo Kinoshita, a graduate student, and I finished two projects. We showed how multivariate record value theory could be used to study the boundary of the convex hull of a multivariate Gaussian sample.

Extremes of moving averages: Collaboration with Richard Davis of Colorado State University continued. We consider the moving average process. We suppose that the distribution of Z_j is regularly varying near 0 and discuss lower tail behavior of finite and infinite linear combinations. The behavior is surprisingly different in the two cases. For finite linear combinations, the lower tail is again regularly varying, but in the infinite linear combinations, the lower tail of the moving average is Γ-varying, ie., it is in the domain of attraction of a type I extreme value distribution in the sense of minima. A sequence of point processes based on the moving averages are shown to converge in both the finite and infinite order cases and suitable conclusions can be drawn from these convergences. The analytic tool used in these investigations is the asymptotic normality of the Esscher transform of the common distribution of the Z's. The analytics complement techniques used with Balkema and Kluppelberg on densities with Gaussian tails and the probabilistic results complement earlier ones with Davis on moving averages when the underlying distribution has a subexponential tail.

With Eric Willekens, a summer 1989 MSI visitor, extensions of the moving average work of Davis and Resnick to random difference equations were made. Certain random difference equations have solutions which are infinite series which appear in the form of moving averages with *random* coefficients. By making moment assumptions on the random coefficients and tail assumptions on the analogue of the Z's, we are able to utilize the moving average results in this new context. The obvious trick is to proceed conditionally on the coefficients having fixed values and then to uncondition using some sort of dominated convergence argument

Max-stable processes: In the investigation of choice theory described above, Rishin Roy and I were able to characterize when a max-stable process indexed by a compact Polish space has upper semi-continuous paths and when the set $M(\omega)$ of points of T which achieve maximum utility consists almost surely of a single point.

Richard Davis and I completed a study of a subclass of the max-stable processes called the max-autoregressive moving average (MARMA) process. These processes are max-stable and because of their comparatively simple form give a good chance of being able to fit data. Prediction is simple in some (but not all) cases and some remarks on estimation are included. Work with Richard Davis shows when a general stationary max-stable process can be represented as a finite max-moving average and characterizes when the process is a permutation process. This work was in preparation for investigations on a Wold decomposition for stationary max-stable processes. A start is made discusing non-linear prediction.

A paper with Laurens de Haan, partly supported by MSI, discusses a generalization of max-stable processes called sup-integral processes. There is a random time change which converts the process I into a homogeneous extremal process. Some results on tail properties of I(t) are given and a simple circumstance where I is a continuous time approximation of solutions of discrete time stochastic difference equations with random coefficients is discussed.

Records: With Charles Goldie, a summer MSI visitor to Cornell, continuing investigations on multivariate records were carried out pursuant to an earlier paper we have jointly coauthored. We have started to investigate the problem of characterizing the limit set of records conditional on the number of records in a compact region going to infinity. The problem seems hard but some progress has been made. If the components are independent, we believe there is a limiting curve representing the records. It appears that the general case will require a large deviation type result for order statistics.

Limit theory and point processes: A study was completed of the connections between point processes and Tauberian theory which complements the techniques in my book *Extreme Values, Regular Variation and Point Processes.* A probabilistic approach to understanding Tauberian theorems is presented which is

applicable when the Laplace transform of a monotone function is being considered. Regular variation at $\infty(0)$ of a function is readily shown to be equivalent to regula- variation of the transform at $0(\infty)$ because of the quality between regular variation and weak convergence of Poisson processes whose mean measures are related to the monotone function under consideration. The method is dimensionless and readily extends to II-variation.

Daren Cline (supported by MSI through David Ruppert) and I formulated a concept of *multivariate subexponential distributions*. The definitions are in terms of vague convergence of measures rather than ratios of distribution tails and allow use of the point process method. With the proper setting, we show that if all one dimensional marginals of a d-dimensional distribution are subexponential, then the distribution is multivariate setting.

In a project with rich possibilities A. Balkema (partly supported by MSI in 1986), C. Kluppelberg and myself formulated and discussed the concept of densities with Gaussian tails. These are densities whose tails look roughly Gaussian. The major use is that this class is closed under finite convolutions. The major analytic tool is to embed such a density in an exponential family and to show the family suitably normalized is asymptotically normal as the parameter of the family tends to ∞. Heavy use is made of convexity theory. We envision this being a most useful class of super-exponential densities and many further problems remain.

A concept of multivariate max-geometric infinite divisibility was defined and studied with Z. Rachev. We give complete characterizations of this class and discuss domains of attraction in a suitable sense. We discuss why such distributions could be useful in modelling extreme events up to the time of a catastrophe.

Thirteen papers acknowledged support of MSI during the contract period.

David Ruppert
School of Operations Research and Industrial Engineering
Naomi Altman, Jiunn Hwang, Martin Wells
College of Engineering, Cornell University

Statistical modeling by smoothing and empirical Bayes techniques: This project is concerned with the section of mathematical models for data analysis, where the data themselves are used to guide the section of the model. The data might be used to select the form of the model, or only in choosing a smoothing or transformation parameter. The key idea is that eventual statistical inference based upon the model must acknowledge that the model-choice was data-based. The project concentrated on smoothing techniques in nonparametric modeling and estimation, and on empirical-Bayes methods. The project has become quite broad, but all work is related to statistical modeling.

Graduate students supported:
Karen Bandeen Roche, Operations Research and Industrial Engineering: Support for fall 1989, Thesis completed August 1990. Thesis title: A receptor-based model for statistical analysis of air pollution data: source appointment with one source unknown. Present position: Department of Biostatistics, John Hopkins.
Mary Dowling, Operation Research and Industrial Engineering: Support for spring 1990. Thesis completed January 1991. Thesis title: parameter estimation in nonlinear regression with covariate measurement error. Present position: Industrial Engineering, Georgia Tech.

Visitors: Summer 1989: Matthew Wand (Rice), Douglas Nychka (N.C. State), J.S. Marron (UNC)., Spring 1990: D. Cline (Texas A&M).

John S. Schlipf
Department of Computer Science, University of Cincinnati
Research Coordinator: **Anil Nerode**

My areas of research include: Logic Programming, Non monotonic Inference, and related modal logic. While at MSI, I completed a draft of the paper The Expressive Power of Locally Stratified Programs with H. Blair and W. Marek for submission to conference. I worked (following discussions with Anil Nerode and Grigori Schwarz) on modal logic formulations for three logic programming semantics and I worked on formulations for non-monotonic difference which seem more natural or corresponding better to actual implementations.

I presented a paper on Representing Epistemic Intervals in Logic Programming to the LPINMR Workshop in Washington.

Paul H. Steen
Department of Chemical Engineering, Cornell University
Edriss S. Titi
Mathematical Sciences Institute

Rayleigh-Benard convection and analog systems are prototypes for understanding the sequence of transitions to more and more complicated flow (spatial and temporal) observed in many systems as more energy is input to the system. Our aim is (a) to reliably capture the dynamic patterns in a regime where spatial and temporal scales compete, (b) to understand the physical mechanism behind the outcome of such competition, and (c) to develop efficient computational means of reliable capture.

Natural convection in fluid-saturated porous media is the particular system studied most intensely, although convection in the related Hele-Shaw system has also been examined. Spatial scales in porous media convection are less constrained than in loop convection but more constrained than in classical Rayleigh-Benard convection. The properties of global existence of solutions (i.e. long-time solutions) and existence of global attractors for the 3D porous media system also place it in a special position mathematically between the reaction-diffusion systems where there is a firm foundation for the global dynamics on a 3D domain and the classical Rayleigh-Benard system (Navier-Stokes plus energy equation with Boussineq approximation) where such a foundation has not yet been established.

In addition to the study of convection systems, Steen acknowledges support as a Cornell '"visitor" with regard to two other research areas involving stability: the hydrodynamics of capillary containment (liquids held by surface tension) and collapse (liquid breakup by surface tension) and the planar-flow spin-casting process by which molten metal is rapidly solidified into a thin ribbon of metal product.

As regards objective (a) above, the reliable capture of complicated dynamics, we have traced the long-time solutions for the 2D porous media system (square domain) from convection onset through periodic to quasiperiodic convection and from the so-obtained branch structure infer transitions to chaos. The spatial structures of these flows are non-trivial and those for the corresponding transitions in a 3D domain are even more complicated. Nevertheless, as regards objective (b), to discover the physical mechanism of these transitions, we have shown that in both 2D and 3D domains the abrupt change to periodic motions occurs due to a traveling wave instability. At higher Rayleigh numbers, at least in the 2D case, travelling waves interact pairwise to generate quasiperiodic motions. At higher Rayleigh numbers still, quasiperiodic motions occur through self-interaction of limit-cycles (parametric instability) and correspond physically to plume formation.

For the Hele-Shaw slot, at least for taller than wide geometries, an oscillatory instability occurs at lower energy inputs and corresponds physically to a "diagonal oscillation" sustained by an exchange of fluid

through alternating vortex connections. From a dynamical systems viewpoint, the instability is a Takens-Bogdanov bifurcation and the presence of a homoclinic orbit allows a route to chaos different from that in the porous media. Much of the bifurcation diagram developed for the Hele-Shaw slot is verified by experiment. Objective (c), the efficient computation of reliable solutions, focuses on implementing inertial manifold ideas for nonlinear Galerkin computations and is carried out in collaboration with E.S. Titi. Here, we have benchmarked the efficiency of approximate inertial manifolds in terms of the number of "dynamic" modes necessary to reliably capture the long-time behavior over a parameter range which includes steady, time-periodic, and quasiperiodic long-time behavior for 2D containers. A similar analysis for the transition to time-periodic motion in 3D containers is complete.

Our analysis of the Benard-analog convection system in 2D and 3D domains has (i) established the dissipative property of the system (i.e., proved existence of an absorbing set), and subsequently, (ii) estimated the Hausdorff and fractal dimensions of the global attractor and for both 2D and 3D cases, has (iii) obtained rigorous estimates of the distance of AIM's from the attractor. These estimates turn out to be exponentially small.

During the contract period four papers acknowledged MSI support. It should be noted that the MSI support for the project on Inertial Manifolds and Nonlinear Convection in Porous Media led to substantial support of this investigation by NSF/AFOSR (DMS 8915672).

Jeffrey E. Steif
Chalmers University of Technology, Goteborg, Sweden
Research Coordinator: **Richard Durrett**

Together with Professor Durrett, I worked on problems in cellular automata. We obtained results on a specific model called the Greenberg-Hastings Model. We also obtained results concerning the crucial value for a threshold voter model. This resulted in the papers "Some Rigorous Results for the Greenberg-Hastings Model" and "Fixation Results for Threshold Voter Systems." Together with Scot Adams, I wrote "An Application of the Very Weak Bernoulli Condition for Amenable Groups" related to abstract ergodic theory. I am in the process of another project with Professor Durrett and involved also in a project with Robert Van den Berg.

Bernd Sturmfels
Department of Mathematics, Cornell University

During the spring and summer of 1991 I pursued an active research program in combinatorics and computational algebraic geometry. In particular, I collaborated on joint projects with the MSI visitors M. Kapranov and A. Zelevinsky. The following seven articles were completed during this period.

1. Quotients of toric varieties, with M. Kapranov, A. Zelevinsky 16 pp., to appear in Mathematische Annalen.
2. Sparse elimination theory, 27 pp., to Appear in Computational Algebraic Geometry and Commutative Algebra D. Eigenbud, and L. Robbiano, eds, Proceedings Cortona (June 1991), Cambridge University Press.
3. Chow polytopes and general resultants, With M. Kapranov, A. Zelevinsky, 32 pp., Submitted to Duke Mathematical Journal
4. On the extension space of an oriented matroid, with G. Ziegler, 20 pp., submitted to Acta Mathematica
5. Cellular strings on polytopes, with L. Billera, M. Kapranov, 8pp., submitted to Inventiones Math.
6. Maximal minors and their leading terms, with A. Zelevinsky, in preparation
7. Multigraded resultants of Sylvester type, with A. Zelevinsky, in preparation.

A main focus of this research lies in the study of discrete invariants of embedded projective varieties. An inportant such invariant is the Chow polypope which was introduced in [3]. In [2] Chow polytopes and

Chow forms are applied to a problem in computer algebra, namely, the development of a refined elimination theory for sparse systems of polynomial equations.

These results are of interest also for researchers in other areas of mathematics. For instance, I was invited to attend a workshop and symposium on Special Differential Equations, in Kyoto, Japan. It is expected that Cornell Combinatorics will have a considerable impact on this field during the next few years.

Moss Sweedler
Department of Mathematics, Cornell University

From June 1986 through October 1991 I worked in the area of computational commutative algebra and real closed fields. In the area of computational commutative algebra, my research used and extended methods related to Buchberger's Gröbner bases. Where Gröbner bases have been primarily used to study questions related to ideals, my research concentrated on developing Gröbner basis techniques for subalgebras. In particular, David Shannon and I developed the first subalgebra membership test. Lorenzo Robbiano and I developed bases for subalgebras which are the subalgebra analogs to Gröbner bases for ideals. The work with Shannon extends to determining the nature of field extensions.

In the area of real closed fields I developed an easy algorithm for determining the relative positions of the real roots of a real polynomial based on the signs of the derivatives of the polynomial at the roots.

During the period from June 1986 through October 1991 I was extremely active in the symbolic computation community, joining the editorial board of the Journal of Symbolic Computation, joining the advisory board for the University of Illinois at Chicago Laboratory for Advanced Computing and heading the subpanel on Algorithms and Theory at the NSF-MSI Workshop on Symbolic and Algebraic Computation: Direction for Future Research, April 29-30, 1988 in Washington, DC.

Levant Tuncel
School of Operations Research and Industrial Engineering, Cornell University

My current research includes a study of computational complexity of preflow-push algorithms for maximum flow problems. The best bound proven on the number of push operations for these algorithms is $O(n^2m^{1/2})$. This bound assumes that for a given node, the algorithm consistently pushes flow along the same arc leaving that node until the capacity of the arc is saturated. We prove the same bound without any assumptions on how to choose the next arc to push flow along.

In joint work with Michael Todd we studied the D_1 triangulation of Dang and using a facetal description we modify it to obtain a more efficient triangulation of the unit hypercube in R^n and then by means of translations and reflections we derive a new triangulation, D'_1 of R^n. We show that D'_1 uses fewer simplices (asymptotically 30% fewer) than D_1 while achieving comparable scores for other performance measures such as the diameter and the surface density. We also compare the results of Haiman's recursive method for getting asymptotically better triangulations from D_1, D'_1 and other triangulations.

Peter Jackson and I studied the Dynamic Lot Size (DLS) model of Wagner and Whitin. It is well-known that the DLS model exhibits a concave objective function whereas the Economic Order Quantity (EOQ) model of Harris and Wilson exhibits a convex objective function. Since DLS model can be considered as a finite horizon version of the EOQ model, it is conceivable to believe that there should be a way of reconciling these two methods. In a recent paper we show that a reformulation of the DLS model along the lines of the EOQ model exhibits a convex objective function provided only that the unit production costs are stationary. A counterexample is provided to show the necessity of the condition.

My current research (joint with Michael Todd) focuses on the asymptotic behavior of interior-point methods for linear programming problems:

We study the asymptotic behavior of interior-point methods for linear programming problems from semi-infinite programming point of view. The work is motivated by Powell's paper showing that for semi-infinite linear programs Karmarkar's algorithm does not necessarily converge to the optimal solution and also by Todd's paper showing which algorithms generalize to the semi-infinite settings. The reason for using this approach is nicely stated by Todd: "Since interior-point methods are supposed to be efficient for large-scale problems, it is natural to consider the limit as one dimension (n, the number of inequality constraints) becomes *infinite*." We study the convergence properties of these generalized algorithms and propose a new potential function which is not necessarily differentiable at all points of the feasible region but has very nice properties as a barrier. We also consider some versions of the new potential function for a finite dimensional case.

Theo P. Valkering
University of Twente, Netherlands
Research Coordinator: **F.C. Moon**

Research focussed upon some aspects of the nonlinear dynamics of planar motion of a driven string. The nonlinearity was provided by a stop positioned near the string, so that the string made contact for high enough driving amplitude. The string was fixed at one end and performed a prescribed periodic motion at the other.

With the stop located at orthogonal distance from the middle of the string, measurements were done on i) Hysteresis, i.e. multistability with respect to the driving frequency and the distance of the stop to the string, and ii) Bifurcations from periodic to chaotic behavior. Coexistance was observed of the linear periodic driven mode with amplitude so small that the string did not hit the stop, and a motion in which the string was hitting the stop. When varying the driving frequency, in the latter class of motions a transition from (quasi) periodic to chaotic motion was observed. There is evidence that the motions in this class can be interpreted as branching of from a nonlinear mode in the nondriven nondamped string. A research paper is in the last stage of preparation.

For a model based on the string equation, general questions of dynamics were investigated. A global attractor with finite dimension was shown to exist. One relevant aspect of the method used is that the system under investigation is Hamiltonian to which a damping is added which is linear in the momenta. A paper on this work is in preparation.

Stephen Vavasis
Department of Computer Science, Cornell University

I have been involved in research in nonlinear optimization and differential equations since coming to Cornell in 1989. My work on optimization includes a number of papers on quadratic programming and general nonlinear programming. Nonlinear optimization refers to the problem of selecting variables satisfying certain constraints to minimize a nonlinear objective function. Nonlinear optimization arises often in engineering design problems. Some of the results include polynomial-time algorithms for local minimization of certain nonconvex quadratic programming problems, complexity results for general nonlinear objective functions, complexity results for nonconvex quadratic programming, and algorithms to give approximate solutions for nonconvex problems. Some of this work was joint with Jorge More of Argonne, and some was joint with Panos Pardalos of Penn State.

Recently, I published a book with Oxford University Press, entitled Nonlinear Optimization: Complexity Issues, which includes many of these results, and also other fundamental results in the field. Some of the

work involved in preparing the book was supported by MSI. In addition, I organized a conference with Panos Pardalos on the subject of complexity issues for optimization, held in Ithaca, March 1991. The workshop was supported by AFOSR and MSI, and featured 17 invited speakers, including two of the plenary speakers (Karmarkar and Tardos) from the summers's ICIAM meeting. The conference was written up in SIAM News, and a formal proceedings will appear as a special issue of Math. Programming.

In the area of differential equations, I have written three papers on the problem of partitioning a mesh among processors (part of this was joint work with Gary Miller and ShangHua Teng of Carnegie Mellon). The goal is to partition the mesh evenly, and simultaneously to minimize the amount of interprocessor communication. Our research identifies a very broad class of graphs occuring in many finite-element problems for which a simple partitioning strategy can be effective.

In addition, I have conducted research on boundary element methods, and presented a paper at the Copper Mountain Conference (to appear in SIAM J. Matrix Analysis) on preconditioning for boundary element methods. The application is a fluid flow problem from Xerox Corp. This work is ongoing.

Since coming to Cornell I have worked with three Ph.D. students: Julio Stern of Operations Research is writing his thesis on a sparse matrix problem occuring in optimization and engineering applications. He is currently a faculty member at the University of Sao Paulo. He was supported primarily by a Brazilain Fellowship, but also received some supplementary support from MSI. I am currently working with Scott Mitchell of Applied Math on the problem of triagulation of nonconvex polyhedral regions in three dimensions. I am also working with Dave Bond of Applied Math on the use of wavelet bases for boundary element methods.

Lars B. Wahlbin
Department of Mathematics, Cornell University
Coordinator for Numerical Anslysis and Computing, MSI, 1985-87, 1988-91
Associate Director for Research, MSI, 1989-91

During 1991 I ran a program on "Numerical Analysis of Integral and Related Equations". Below I list the six visitors under this program and give a brief discussion of what we did.

Phil Anselone: Short time visitor; worked with I. Sloan (below).

Chen Chuanmiao: He and I started work on pointwise error estimates for the numerical solution of partial integro-differential equaitons.

Donald French: He and I concluded work on the numerical solution of visco-elastic problem. See MSI report 91-49.

Gabriel Gatica: He worked mainly on his own with occasional input from Bramble, Sloan and me. He produced a number of MSI reports.

Ian Sloan: Sloan, Al Schatz, and myself worked on the local behavior in numerical solutions of integral equations, and on superconvergence. This work will continue — it is only in its initial stages. Apart from this, Sloan finished up quite a number of papers on his own.

Vidar Thomee: A long-time collaborator of mine, this time we worked on the long-time behavior of numerical solutions of partial integro-differential equaitons. A report is in preparation.

During the Spring 1991 semester, I ran an "informal seminar" in conjunction with this project. During the period 1986-91, thirteen publications of mine acknowledge MSI support. In particular, three publications are direct consequences of MSI-sponsored visits by M. Crouzeix, Y. Lin, and D. French.

A graduate student of mine, Todd Peterson, enjoyed MSI support during 1998-90. Working on behavior of the discontinuous Galerkin method, he took his Ph.D. in August 1990 and contributed to MSI Tech. Rep. 90-26. I gave two tutorials at Army labs on "Finite Element Methods," and, together with MSI post-doc Bruce Wade, gave advice on numerical peculiarities for nutating liquid-filled rockets.

Richard Zippel
Department of Computer Science, Cornell University

I arrived at Cornell in November of 1988 and have been partially supported by MSI since September 1989. During this period I worked on a variety of problems of both a theoretical and practical nature. Each of these problem areas is discussed below. The first two sections deal with my work on the fundamental algorithms of symbolic computation, interpolation, and functional decomposition. Section 3 discusses a symbolic computation substrate that we have developed. One of the problems this substrate has been applied to is the generation of dynamical systems for problems in fluid dynamics. This is discussed in Section 4. Finally, some of my work in computer architecture is mentioned in Section 5.

Interpolation: Many algorithms in symbolic computation avoid problems of intermediate expression swell by using interpolation schemes. Ultmately, these techniques turn on the following problem. Given a black box that can return the value of a function at any point and some information about the function represented by the black box (e.g., it is a polynomial in n variables each of degree less than d), determine the function itself. (Notice that the learning questions of Rivest and Valiant are special cases of the interpolation problem.) This approach was used successfully in probabilistic algorithms starting from my Ph.D. thesis in 1979. Whether intrepolation of polynomials can be done in deterministic polynomial time has been an open question ever since. Nearly simultaneously, ben Or and Tiwari and myself provided (different) positive answers to this question when bounds are known on the number of non-zero terms in the polynomial. Ben Or and Tiwari's result is slightly faster than mine, but mine works over fields of any characteristic. Careful analysis of the interpolation problem also revealed that there existed interpolation problems, which use oracles, that could not be solved in deterministic polynomial time, but which could be solved in random polynomial time.

Functional Decomposition: An important problem in Symbolic Computation, which has not been completely resolved, is determining when a function $f(x)$ can be written as the composition of two function $f(x) = g(h(x))$,. Many problems are much easier when such a decomposition exists including: expressing the roots of $f(x)$ in terms of radicals, evaluating $f(x)$ at a value of x, finding numerical solutions of $f(x)$, etc. In addition, it is intrinsically an elegant problem. This problem was first discussed by Ritt for the case of $f(x)$ a polynomial. Our publication of an algorithm for functional decomposition of polynomials in 1986 prompted a flurry of work. All of these papers considered the case of functional decomposition of polynomials, and even in this case no polynomial time algorithm was developed for polynomials over finite fields. The case of $f(x)$ a rational function has always seemed to be much harder because there are no obvious bounds on the degrees of $g(x)$ and $h(x)$. (In the polynomial case, $\deg f = (\deg g)(\deg h)$.) Recently, we developed a new polynomial time algorithm for functional decomposition that is valid for polynomials and rational functions over arbitrary fields of any characteristic. This work, and the extensions that are still being investigated, have lead to a number of fascinating questions in theory of algebraic fields, abelian varieties, and linear groups.

Weyl: In order to support some of our experimental work, we found it necessary to build a small computer algebra system that was sufficiently extensible. This system, called Weyl is aimed at people that wish to incorporate symbolic techniques into a large computational system. This contrasts with systems like Mathematica and Maple that are intended to be used more as calculators. Unlike Mathematica and Maple, but like Scratchpad, Weyl's organization is functorial. This means that rather than writing code for polynomials over the integers, we have modules that implement polynomials over an arbitrary ring. These modules can then be used to build up the rings and fields over which one wants to compute.
The type system that arose as part of Weyl has some interesting properties, because we need to deal with partial information about the type of an object. For instance, we might know that an algorithm can be applied to a polynomial without needing to specify the polynomials' algebraic domain. Weyl is being actively used by John Hopcroft's modeling and simulation group in the Computer Science Department here at Cornell and by Harris, Co. in Melbourne, FL for work in digital modem design. Another application of Weyl is discussed below. In addition about a dozen copies of Weyl have been distributed around the country for further study, enhancement and possible use.

Fluid Dynamics: We have been developing symbolic techniques to generate differential equations that model physical systems, and using symbolic techniques to make the equations easier to solve. One problem we have been studying with graduate student Steve Rapkin and students of Prof. John Lumley in Mechanical and Aerospace Engineering is the underlying coherent behavior of the turbulent flow of a fluid near a boundary. Using the proper orthogonal decomposition technique, as first suggested by Lumley, the stochastic velocity field of fluid can be decomposed into deterministic eigenfunctions (the coherent structures of flow). Applying a Galerkin projection of the Navier-Stokes equations using these eigenfunctions, we can then develop ordinary differential equations for the amplitudes of the eigenfunctions in the velocity field. By studying the qualitative properties of these ordinary differential equations we hope to gain a better understanding of the qualitative behavior of the fluid. The deterministic eigenfunctions are only known as solutions of a Fredholm integral equation. To simplify the code for generating the Galerkin projection, with graduate student Steve Rapkin, we have introduced the concept of a *sampled function* into Weyl. Such a function is known numerically at a few sample points. Arithmetic with these objects is done in terms of their numerical values (sometimes with resampling to preserve accuracy), but the user can view them as symbolic objects. This approach dramatically simplifies the complexity of performing the Galerkin projection. Thus, with only a few pages of code, we can quickly generate differential equation generators and solvers for some extremely complex dynamical systems. This is software now being tried out by some of the students in Lumley's group. This work was presented at a workshop on symbolic/numeric techniques and will appear in its proceedings.

Data Structure Accelerator: Parallel computer architectures are usually divided into the SIMD (single instruction multiple data, e.g. Connection Machine) and MIMD (multiple instruction multiple data, e.g., Intel Touchstone) classes. Starting with our work at MIT with Reif and Sodini, we have been interested in approaches to SIMD computation that can be integrated with other computational models, including workstations and MIMD architectures. At Cornell we have greatly refined our approach to single instruction multiple data computer architectures. A new high level language has been developed that makes the specification of the mixed SIMD and MIMD computations much easier. The architectural model has been streamlined significantly and we have begun exploring the advantages of a two dimensional interconnection between the processing elements over the one dimensional scheme we are currently using. We have investigated uses of in a number of problems in computational geometry. In general this approach has lead to sub-linear speedups but a dramatic reduction of the complexity of the algorithm.

Postdoctoral Research

Roger Cracknell
Work in collaboration with Professor Keith E. Gubbins

Theoretical Studies of Adsorption in Microporous Materials

In the last decade, a new class of molecular sieves, the aluminophosphates, have been developed. They have the stoichiometry $AlPO_4$ and the structure consists of alternate tetrahedral aluminum and phosphorous atoms bridged by oxygen atoms; they thus bear structural similarities to the aluminosilicate zeolites. Any sturcture with the stoichiometry $AlPO_4$ is electrically neutral whilst this is only ture of zeolites containing silicon as the tetrahedral atom.

Like aluminosilicates, aluminophosphates form extended 3D sturctures with large pores. The pore size can be characterized by the number of tetrahedral atoms in the ring. Aluminophosphates have been synthesized with 10, 12 and 14 membered ring pores ($AlPO_4$-11, $AlPO_4$-5 and $AlPO_4$-8 respectively) using a patent of Union Carbide. More recently an 18 membered ring pore, VPI-5, has been synthesized by Davis and coworkers.

The larger ring aluminophosphates are significant in that the pores are larger than any aluminosilicates that can currently be made, thus offereing new possibilities as adsorptives and molecular sieves.

Because of the high crystallinity, the pores in aluminophophates are regular and well defined. The pores tend to be straight with no interlinking. Thus, the adsorption behavior should in theory be devoid of any of the properties which might be associated with networking or pore blocking effects; consequently the theoretical framework in which adsorption in alumiophosphates may be considered consists of adsorption in a single pore. Moreover, the absence of counter ions in aluminophosphates makes them easier to model than aluminosilicates.

We have employed two approaches to the study of adsorption in aluminophosphates, both using grand canonical ensemble Monte-Carlo computer simulation. In the first approach, we have attempted to model the adsorption of Ar in VPI-5, $AlPO_4$-8 and $AlPO_4$-5 using models based on their x-ray sturctures. We are able to reproduce the shape of the experimentally obtained VPI-5 isotherm quite well. Not surprisingly, the maximum theoretical adsorption that we predict is somewhat greater than that observed in practice. One explanation is that any real sample will be composed of a finite number of grains and so the microporous structure will not be a phase transition (to $AlPO_4$-8) when the hydrated material is calcined. Small regions of $AlPO_4$-8 may serve to block the pores, thus reducing the maximum adsorption capacity. There is increasing evidence inthe literature from NMR, x-ray and neutron scattering, and electron microscopy that this is indeed what happens. The simulation and experimental isotherms for $AlPO_4$-8 show much larger discrepancies indicating that the real material is very disordered. Simulation studies of $AlPO_4$-5 are still in progress.

In the second approach we do not model any atoms discretely, but view the pore wall material as a continuum and study the effect of pore size and cross-sectional shape on the adsorption properties. The adsorbate molecule studied thus far is methane which is of the utmost commerical significance. One goal of this work is to be able to make statements about optimal pore size and shape for methane storage. We have found this to occur for a material with a radius of between 1-1.5 molecular diameters depending on the storage temperature and pressure. We have compared adsorption isotherms for pores with circular and hexagonal cross sections. At low temperatures, we have found that for pores of identical cross-sectional areas, there can be a large difference in the simulated adsorption isotherms if the molecules can pack in an optimal fashion in one of the geometries, but not the other. We will extend this work to designing theoretical porous materials for gas separation, given two spherical molecules of differing sizes.

Juan Elezgaray

Report on attendance at the Third School on Dynamical Systems and Turbulence (April 28, 1991 - May 11, 1991), in the USSR: I lectured on Wavelet analysis of the dynamics of coherent structures in the Kuramoto-Sivashinsky Equation.

The scope of this conference was very broad; the program included the presentation of the latest achievements of Soviet scientists in nonlinear dynamics and turbulence. Concerning my specific field, namely the application of the wavelet basis to the study of nonlinear partial differential equations, the present level of advancement in the U.S.S.R. is clearly in a primary stage. Only the work presented by Dr. A. Praskovsky (Central Aero-Hydrodynamic Institute, Zhukowsky, Moscow) was clearly related to this subject. He explained the results obtained in the measurement of the $f(\alpha)$ spectrum of the longitudinal component of the velocity field obtained in wind tunnel experiments. His results, though more accurate, turned out to be in good agreement with those obtained previously by Y. Gagne and E. Hopfinger (Grenoble, France). Even though the multifractal ($f(\alpha)$ based) approach to fully developed turbulence is of theoretical interest, we believe that more effort should be devoted to the more challenging problem of analyzing the properties of the Navier-Stokes equations using orthogonal wavelet bases.

The main theme of my talk was actually related to this: I explained how to build a stochastic, low dimensional model of the ID Kuramoto-Sivashinsky equation using Galerkin-like projections onto orthogonal wavelet bases (a detailed version of the preliminary results obtained in this direction is given in the proceedings of the DARPA conference on Wavelets and Applications, June 3 - 7, Princeton). The results obtained thus far are very promising in the sense that they provide an easy framework in which to understand the dynamics of the (localized) coherent structures observed in a wide variety of situations, going from the simple example of the Kuramoto-Sivashinsky equation to the fully developed turbulence obtained in the boundary layer problem. Lumley, Holmes and coworkers showed in a clever paper (JFM, vol. 192 (1988) 115) how the proper orthogonal decomposition is able to capture the most relevant dynamical features of the later flow. The next step in our research project will be to replace the later decomposition by the wavelet decomposition. The soundness of this procedure is discussed in the above paper.

During this period my research has been devoted to two main themes:

(1) Wavelet analysis of the motion of coherent sturctures in turbulent flows.
(2) the modeling of pattern formation phenomena in reaction-diffusion chemical systems.

As far as the first subject is concerned, it is now widely accepted that the existence of coherent motions plays an important role in the production of turbulence. Several approaches have been suggested to give a quantitative content to the vague notion of "coherent sturcture." Among them, the proper orthogonal decompositon (Lumley, 1970) has been successfully applied to the boundary layer flow (Aubry et. al., 1988), explaining the intermittent bursting phenomenon as the result of local interactions between vortices. However, this method does not explain in a natural way the spatial localization of the coherent structures in the homogeneous (tranlationally invariant) directions, where the proper orthogonal decomposition becomes identical to the Fourier decomposition.

As far as the second theme is concerned, my work has been essentially the continuation of my preceding collaboration with A. Arneodo (CRPP, Talence, France) on the study of a model reaction-diffusion system for the pattern formation phenomena observed in the open Couette flow reactor, an experimental device developed simultaneously in the CRPP and by H.L. Swinney and colleagues in Austin (Texas).

Oliver Harlen

During my period as an MSI research fellow (from November 1990 to August 1991) I have been working with Professor Donald Koch of the School of Chemical Engineer'.ıg on predicting the flow behavior of suspenstions of fibers in polymer solutions. Fibers are often added to polymeric materials during molding in order to improve the physical properties of the molded material. These properties depend critically on the orientation of the fibers, and consequently there is much interest in being able to predict the fiber orientation. Although the behavior of fiber suspensions in Newtonian fluids has been studied widely, relatively little theoretical work has been done on fiber suspensions in non-Newtonian fluids, such as polymer solutions. Previous theoretical studies of fibers in polymeric fluids by Leal (1975 Journal of Fluid Mechanics) and Goddard (1976 Journal of Fluid Mechanics) consider the case of small velocity gradients when the deformation of the polymer is small. Our work considers the opposite case of large velocity gradients when the polymer can become highly deformed by the flow. Allowing the polymer to become highly deformed greatly increases the complexity of the system, and in order to simply the problem we restrict our analysis to dilute concentrations of fibers and polymers. Both shear and extensional flow have been investigated.

In shear flow, the velocity disturbances caused by fibers produce a dramatic increase in the extension of the polymer over that found for the polymer solution alone. This in turn leads to an increase in the viscosity of the suspension at high shear rates. The non-Newtonian stresses exerted by the stretched polymers also modify the motion of the fibers. Both our results, and those of Leal for small flow rates, predict that the orientation of the fibers will drift towards the axis of vorticity, as is observed in experiments.

The addition of fibers to a Newtonian fluid produces a large increase in extensional viscosity. However, we find the addition of fibers to a polymer solution produces a much smaller increase inthe extensional viscosity. The presence of the polymer molecules alters the form of the velocity disturbance caused by the fibers resulting in a decrease in the orientatinal dispersion due to fiber-fiber interactions.

In addition to this work on suspensions of fibers in polymer solutions, we have also made a preliminary study of the sedimentation of a suspension of fibers in a Newtonian fluid. A single fiber sediments without rotating, but in a suspension the velocity distrubances produced by neighboring fibers cause the fibers to rotate. By calculating the average effect of these interactions we are able to predict the orientation distribution of the fibers for a particular range of fiber concentrations.

Zbigniew Leyk
Institute of Informatics, Warsaw University, Poland
Research Coordinator: **J. H. Bramble**

My main field of research is the numerical solution of linear partial differential equations (pde), in particular, new effective methods for solving such equations.

Usually to solve a pde we use the finite element or the finite difference method. The resulting system of equations is sparse (the matrix of this system has a few nonzero elements in a row), ill-conditioned and the number of unknowns is large (at least several thousand). We will call this system the **fem** system. There has been extensive research in the study of efficient algorithms for solving **fem** systems. If we try to solve a **fem** system directly, we see that it tends to become rather expensive when applied to two- and three-dimensional differential problems. Another idea is to solve this system iteratively using iterative methods. Classic examples are Gauss-Siedel and Jacobi iterations. But in practice they are also very expensive and slow.

To find the solution of the **fem** system as cheaply as possible using an iterative method we must transform this system by applying so-called preconditioning. Good preconditioners form new systems of

equations which have small condition numbers independent of the number of unknowns. Among the many algorithms using preconditioning for solving the **fem** systems that have been studied in recent years, we have multigrid and domain decomposition methods. In these methods preconditioning is chosen by solving some appropriate subspace problems. There is evidence indicating that there exists a connection among different iterative algorithms used for solving the **fem** systems, and attempts to establish a unifying theory have been undertaken. Multigrid and domain decomposition methods are extensively examined nowadays and new variants of these methods are formed, because they allow one to solve a pde very fast in a very efficient manner (relatively small memory requirements, possibility of parallel computations).

A theoretically good method must be tested as to how it behaves in practice. It is necessary to create a package of numerical procedures or to modify an existing one to implement the method. To implement either the domain decomposition or multigrid method it is necessary to create a very sophisticated computer code. According to a suggestion of Prof. J. Bramble, with whom I actively interact all the time, I have created such a package of numerical procedures for studying both methods for 2-dimensional elliptic problems. The basic version was formed in May 1990, the second version with many corrections and additions to the previous one was formed in August 1990. Difficulties with maintaining and introducing changes into the code resulted in developing the third version of the code. I used the object-oriented programming technique, which divides a program into modules (objects) that perform specific tasks, contain both data and instructions, and can be re-used in different combinations (for instance two- and three-dimensional differential problems, different regions, etc). Re-usable code allows one to reduce software development and maintenance time. Moreover, it allows computer users who are not programmers to tailor their own software to preform complicated tasks simply by using pre-designed modules. I used also dynamically allocated and deallocated vectors and matrices, so that code can even run on machines with relatively small memory. This part of the code is described in [1].

Independent of creating the code, I worked on a new domain decomposition method for solving nonsymmetric pdes with a positive definite symmetric part. This method was presented at the Eight Army Conference on Applied Mathematics and Computing (Cornell University, 19-22 June, 1990) and it was published as a MSI Technical Report '90-69 (see [2]). The code allowed me to include numerical results in the paper. For symmetric positive definite pdes there exists a good theory of multigrid and domain decomposition methods. But for nonsymmetric and indefinite pdes (e.g. convection-diffusion or streamline diffusion equations) such a theory is being developed. In the paper (see [2]) I proposed and analyzed a domain decomposition method for solving nonsymmetric (but positive definite) pdes. This method does not require any restrictions on a coarse grid contrary to other domain decomposition methods for the same problem. For some problems it is very important not to have any restrictions on the coarse grid.

In May 1991, working together with Prof. J. Bramble and Dr. J. Pasciak from Brookhaven National Laboratory, we wrote a paper on a new efficient multigrid method for solving indefinite and nonsymmetric pdes (see [3]). Now, also together with Prof. J. Bramble and Dr. J. Pasciak, I am working on a paper on a new multigrid method for solving boundary integral problems. It is a new efficient method for solving boundary integral problems and there are few papers on this subject.

[1] "Basic linear algebra functions for C language usage (C-BLAF)", Tech Report '91-24, MSI, Cornell University.

[2] "Domain Decomposition methods for nonself[illegible]int operators", Tech. Report '90-69, MSI, Cornell University.

[3] "Iterative schemes for non-symmetric and indefinite elliptic boundary value problems", with J. Bramble and J. Pasciak, to be published.

[4] "Multigrid algorithm for boundary integral operators", with J. Bramble and J. Pasciak, in preparation.

Graduate Student Reserach

Bruce Anderson

I am investigating questions concerning the signs of derivatives of real-valued functions in general and polynomials for computer algebra applications. I have discovered that there are restrictions on the location of zeros of derivatives of polynomials beyond those arising from Rolle's theorem. This past summer I investigated further restrictions, seeking to find emerging patterns, and to unify the method of finding such restrictions. Ultimately, I would like to 1) characterize all restrictions on the relative placement of real roots of differentiable functions and successive derivatives; 2) investigate the possibility of sharper results for polynomials of fixed degree; and 3) look into higher Rolle's theorems extended to the complex plane and general n-dimensional real and complex functions.

Rolle's theorem easily extends by iteration to the case where n roots of the function implies a root of the n-1st derivative. We present an example of a higher order Rolle's theorem for a function having five roots where conditions on the position of the roots of f'' relative to the roots of f and the position of the roots of f' insure that $f^{(5)}$ has a root. Iterated Rolle's thorem would only guarantee that $f^{(4)}$ has a root. The proof is an application of Taylor's formula. This thorem is one of a familty of such higher-order Rolle's theorems.

John Dalbec

This past summer I studied and did research in invariant theory under the direction of Bernd Sturmfels, with particular attention to the problems of finding a standard basis for the ideal generated by the Cayley-Menger determinants in n-dimensional Euclidean space. This problem generalizes the Second fundamental Theorem of vector covariants described below.

The First Fundamental Theorem of vector covariants of a subgroup G of FL(n,F) gives a generating set for the F-algebra of covariants of G. Given a finite set of these generators, the Second Fundamental Theorem gives a generating set for the ideal of algebraic dependences among the generators in the finite set.

Dr. Sturmfels and Neil White have extended the Second Fundamental Theorem for GL(n,f) (corresponding to projective (n-1)-space) to obtain a standard basis for the algebraic dependence ideal, and have further shown that reduction to normal form with respect to this basis is equivalent to the classical straightening algorithm.

I hope to be able to do the same for the Euclidean group of isometries of (n-1)-space. In order to do this, I will need to understand the Fundamental Theorems of vector covariants for this group. Dr. Sturmfels has recommended that I prove these theorems independently by modifying the proofs from the case of the special orthogonal group of rotations about the origin.

Heike Dengler

The broader field of my research is option pricing theory. Mathematically, this involves stochastic integration and convergence of stochastic processes. The idea behind option pricing is to find a suitable market model, and to come up with the value for options, as well for other derivative securities, within this model.

Having fixed a market model, one uses stochastic integration to determine the option's value. This approach is best described in the papers "Martingales and Arbitrage in Multiperiod Security Markets" (1979) by M. Harrison and D. Kreps and "Martingales and Stochastic Integrals in the Theory of Continuous Trading" (1980) by H. Harrison and S. Pliska. In another setting a market model is not fixed but

rather one looks at the approximation of one model by others. Mathematically, this means, one examines the convergence behaviour and properties of stochastic processes, with each stochastic process describing the option's value in one model of the series being looked at. Papers which describe this approach are "From discrete to continuous time finance: Weak convergence of the financial gain process" (1988), D. Duffie and P. Protter; "Convergence from discrete to continuous time financial models" (1989), H. He.

I'm interested in this field, as it combines mathematics with down-to-earth questions. Having always been interested in integration theory, I'm able to investigate this part of mathematics further. As for finance, it's exciting to find out what questions can be approached and what insights achieved by mathematical methods. To understand the interaction of Mathematics and Finance and to get an idea, what the whole field is about, I'd recommend reading the book "Option Pricing" by Robert Jarrow.

Erich Friedman

I obtained my Ph.D. from Cornell in May of 1991, and the Mathematical Sciences Institute funded me during the summer of 1991. During this time, I continued my research in interacting particle systems, and this resulted in two papers: "First Passage Percolation on a Poisson Lattice" and "First Passage Percolation on a Nonhomogeneous Latttice." My research concerns particle systems. In particular, I am currently studying various versions of a first passage percolation model on a random lattice.

The simplest is a growth model on a homogeneous Poisson point process on $\mathbf{R}^d$ of intensity λ. Usually in this model, the set of infected sitesgrows linearly and has an asymptotically spherical shape. The only exception is in $d = 1$ for $\lambda > 1$, for which the growth is sublinear. These results generalize to nonhomogeneous models, both on a random lattice and on the more usual integer lattice. The goal for these processes is to prove so-called "shape theorems" for the set of infected sites. This summer, I put the finishing touches on papers about both the homogeneous and nonhomogeneous models.

Fu-shing Hsieh

Fu-shing Hsieh was supported by MSI through a graduate student fellowship between 1987-1988. Due to the fellowship, he was free from his T.A. duties at the Cornell Math Department. He was able to take the opportunity to visit Stanford University with Professor J.T. Hwang of the Dept. of Mathematics. They have done several joint research papers, one of which is written up as an MSI Technical Report.
Fu-shing Hsieh graduated in the summer of 1991. His thesis title is: Diagnostic Tests in a Nonparametric Setting.

Susan Lee

During this past summer I studied stochastic partial differential equations because I wish to write a PhD dissertation on parabolic SPDE's. Toward this end, I read J.B-Walsh's paper entitled, "An Introduction to Stochastic Partial Differential Equations," Lecture Notes In Mathematics, Springer-Verlag, 1984. As time permited, I also read a paper by Tokuzo Shiga entitled, "Two Contrastive Properties of Solutions for one dimentional Stochastic Partial Differential Equations."

With Dr. R. Durrett, I investigated the behavior of the solution to the stochastic partial differential equation. In particular, I worked to prove that the solution has the propagation of compact support property (PCSP) when alpha is less than one. Hitherto, it was known only that PCSP exists for alpha less than or equal to one-half.

Niandong Liu

My research in the 1991 MSI summer project was concerned with a certain class of combinatorial problems arising in a geometric setting. The main tools to be used are commutative algebra and homological algebra. A particular problem is to determine the number of faces in a convex polytope by studying the so-called face ring or Stanley-Reisner ring. I am interested in the study of the structure of this ring when viewed as a module over the polynominal ring. We will investigate the relations among the freeness of the module, condition of the ring to be Cohen-Macaulay and the combinatorial as well as topological properties of the original convex polytope. Also of interest is the study of polyhedral subdivision. Here the tools of homological algebra and computational algebra will be used. I expect to obtain some results in commutative algebra through the study of convex geometry.

Sungchul Lee

I studied a continuous time stochastic process during the past summer. This study was an extensive survery rather than a study of special details. I studied Kolmogorov's consistent theorem, Chentkov's theorem, Donsker's invariance principle, and other topics. There is the possibility that I may go into some special topics, e.g., Brownian Motion or Diffusion Process etc. I started with a lecture note given by S.R.S. Varadhan at NYU (1967-68)

Alyson Reeves
Research Coordinator: **Michael Stillman**

Specific Area of Research: Algebraic Geometry, specifically, Hilbert Schemes and Borel-fixed ideals.

I proved two major theorems about the Hilbert Scheme: one concerning where certain ideals lie on the Scheme, the other giving a bound on the diameter of the shceme. I also completed the implementation of a preliminary version of a computer program to compute the state polytope of an ideal. I gave a talk on this subject at the Army Conference in Minnesota on June 19, 1991. And I began writing my thesis.

During the spring semester of 1991, my research in Algebraic Geometry focused on determining the diameter of the Hilbert Scheme as measured in components. This diameter turns out to be surprisingly small and is directly related to the dimension of the schemes parametrized by the given Hilbert Scheme.

I also explored questions on term orderings, and discovered a counter-example to the long-standing belief that the lexicographic order always yields generators of the Grobner basis of the highest degree for an ideal in generic coordinates. Subsequently, I submitted a paper entitled, " The Worst Order Is Not Always The Lexicographic Order" to the SIGSAM Bulletin. Along similar lines, I constructed examples of odd phenomena that can occur with the state polytope (one combinatorial structure on the Hilebet Scheme), which have led to greater insight into its structure.

This past May I received a Special Masters in Computer Science, and in June I gave a talk entitled "Combinatorial Structure of the Hilbert Scheme" at the Ninth Army Conference onApplied Mathematics and Computing.

During the Spring, I also implemented an algorithm to compute the state polytope of an ideal. However, for any but the smallest of examples, the current algorithm runs into numerical problems. There is however, an algorithm to compute a dual structure called the Gröbner fan, and this algorithm does not seem to be subject to the same numerical problems. Currently I am investigating ways to implement the Gröbner fan algorithm.

S. Sarangarajan

Let Δ be a pure d-dimensional simplical complex embedded in $\mathbf{R}^d$. For $m,r \geq O$, let $C^r_m(\Delta)$ denote the set of all piecewise polynomials $f : \Delta \rightarrow \mathbf{R}$ such that

(i) $f|_\sigma$ is a polynomial of degree atmost m for each $s \in \Delta$.

(ii) f is smooth of order r.

These functions are called splines. It can be shown that $C^r_m(\Delta)$ is a finite dimensional vector space over R. We study the structure of $C^r_m(\Delta)$ using Homological algebra. The homological approach was developed by Billera in his proof of a conjecture of Strang about $\dim C^1_m(\Delta)$ for a generic embedding of a planar 2-manifold Δ. Another possibility is to study the space of continuous linear functions over non-simplicial decompositions of a d-dimensional region in $\mathbf{R}^d$ using homological algebra. This is a problem that has considerable geometric interest.

We also explore the interaction between combinatorics and commutative algebra by studying the face ring of a simplicial complex. More specifically, let Δ be a d-dimensional simplicial complex defined on the vertex set $V = \{v_1, v_2, \ldots, v_n\}$. The face ring of Δ is given by $A_\Delta = K[x_1, \ldots, x_n]$ where K is a field and $I_\Delta = \langle x_{i1} \ldots x_{ik} \mid \{v_{i1}, \ldots, v_{ik}\} \notin \Delta \rangle$.

In 1971 McMullen proved the Upper Bound Theorem for convex polytopes. This theorem gives an upper bound on the f-vector of a convex polytope. Stanley used the face ring to extend this theorem to general triangulated spheres. We use these results in studying the set of all f-vectors of d-dimensional convex polytopes. There is considerable interest in describing this set completely, but this has remained an open problem.

Yuan-chung Sheu

We investigated general Markov processes with branching and their limit case-superprocesses which describe the situation with the number of particles large, the mass and the life time of each particle small. Such kind of model was introduced first by S. Watanabe and was studied by Dawson, Dynkln, Perkins and other investigators. My research will focus on the following three directions:

(1) construction and characterization of the most general superprocesses. Something in this direction has been done by Dawson, Fleischmahn, and Dynkin.

(2) absolute continuity problem of the state of the superprocess $X\sigma$, where σ is a stopping time.

(3) relation between path property of superprocesses and nonlinear partial differential equation. Processor Dynkin has made significant progress in this direction.

Pieter J. Swart

The final year of my graduate studies was sponsored by an MSI fellowship. I would like to express my appreciation for the generous financial support by MSI during a critical period of my Ph.D.

This report describes the research done during the final year of my graduate career at Cornell, while being supported by an MSI fellowship. A more complete description is contained in my Ph.D. thesis [5], a copy of which was sent to MSI.

My research, jointly with my advisor Professor Philip Holmes (T&AM, Cornell), concentrated on problems related to the creation of microstructure in nonlinear partial differential equations modeling material phase transitions. The long-term dynamical behaviour of these dissipative PDEs is thought to represent the equilibrium states of deformations associated with the creation of microstructure in certain alloys, such as the thermally induced Austenite-Martensite mixtures observed in Indium-Thallium. This process is modeled by infinite dimensional evolution equations and analyzed using the methods of Dynamical Systems theory (cf.[1] for background and additional references). These systems have a wealth of equilibria which the solution dynamically explores in a complicated fashion, in an effort to approach the minimum energy. Such solutions, although without any recurrent or periodic behaviour, display a subtle dependence on the initial configuration that is very different from that of chaotic finite dimensional dynamical systems. This results in challenging new theoretical and numerical problems, which we believe can provide insight into the process of pattern formation and the eventual control of strength and response properties of these interesting materials.

We investigated several one-dimensional models displaying varying degrees of the above behavior and the results are summarized in [2]. A more explicit numerical example of the sensitive dependence on initial conditions is presented in [3]. Numerical experiments on the IBM3090 supercomputer of the Cornell Supercomputer Facility provided significant insight into the complicated behavior of these systems.

We also investigated the general n-dimensional problems of modeling phase transitions within the framework of nonlinear viscoelasticity. The theoretical part of our research concerned the investigation of a novel transformation of the problem devised by Rybka (cf. [4]). This transformation is the n-dimensional generalization of transformations underlying our analysis of one-dimensional models and enabled Rybka to establish existence (for the first time) of solutions to the three-dimensional equations of viscoelastodynamics that can undergo phase changes. The higher dimensional problem is much more interesting in that it involves projections of Helmholtz type that are closely related to those used in the study of incompressible fluid flow. By exploiting this transformation and focusing on the case of two dimensional anti-plane shear, we hope to gain some understanding of the dynamical evolution of the complex crystal-like microstructure that is observed in experiments (and absent from the one-dimensional models). Along this line, we have established the long time existence and uniqueness of a class of insightful problems, at the same time generalizing the derivation of Rybka's transformation. This led to some rather deep, but interesting, new mathematical problems which we are currently investigating.

We also pursued a numerical investigation of the anti-plane shear problem using the IBM3090 supercomputer of the Cornell Supercomputing Facility. Finite difference algorithms were developed and used to produce a video animation [6] showing the dynamical evolution of microstructure. The insights provided by this video have aroused considerable interest amongst other researchers in this field. It was shown by Phil Holmes at the Conference "Contemporary Developments in Solid Mechanics" at CalTech in March 1991. It was also shown by John Ball of Heriot-Watt University (Edinburgh, UK) at the International Congress on Industrial and Applied Mathematics in Washington,D.C. during July 1991. As a result of this, several other researchers are now thinking about these issues. During this time we also started our development of an alternative algorithm using spline-based wavelets. To our knowledge this represents the first use of wavelets for the solution of a two-dimensional partial differential equation. This work is still in progress.

References:
[1] J.M.Ball (1990) Dynamics and minimizing sequences. Problems Involving Change of Type (K. Kirchgassner, Editor.) Springer Lecture Notes in Physics 359, 3-16, Springer Verlag, New York, Heidelberg, Berlin.

[2] J.M. Ball, P.J. Holmes, R.D. James, R.L. Pego and P.J. Swart (1990) on the dynamics of fine structure. J. Nonlinear Science 1, 17-70.

[3] P.J. Holmes and P.J. Swart (1990) A Mathematical Cartoon for the Dynamics of Fine Structure. Proceedings of the Eighth Army Conference on Applied Mathematics and Computing, Ithaca, 1990.

[4] P. Rybka (1990) Dynamical modeling of phase transitions in solids by means of viscoelasticity in many dimensions. Ph.D. Thesis, Courant Institute of Mathematical Sciences.

[5] P.J. Swart (August 1991) The Dynamical Creation of Microstructure in Material Phase Transitions. Ph.D. Thesis, Cornell University.

[6] P.J. Swart and P.J. Holmes (1991) Dynamics of phase transitions in nonlinear viscoelasticity (video animation). Cornell National Supercomputing Facility.

Judith Underwood

My area of research is constructive mathmatics. I am currently studying ways of expressing the algorithmic content of classical proofs. Goundbreaking work has been done in this area at Cornell by Chetan Murthy, inspiring other researchers including Jean-Yves Girard. Murthy's work is in constructive arithmetic, while Girard's is in intuitionistic predicate calculus; I am working on understanding the relationship between the two approaches. In a related area, I am looking for a more direct computational interpretation of classical mathematics through new notions of realizability and new model theories.

Yaoping Zhang

During the period when I received support from MSI, I tried to learn something about the state polytopes of homogeneous ideals, introduced by D. Bayer and I. Morrison (J. Symbolic Computation (1988) 6, 209-217). Also, under the direction of Professor Bernd Stermfels, I worked in this area. For instance, characterization of homogeneous ideals whose state polytopes are of dimension one would be a very meaningful work because of the wonderful relation between a homogeneous ideal and its state polytope That is to say, there is a canonical bijection between the set of the Gröbner bases of a homogeneous ideal and the set of vertices of its state polytope.

MSI/US Army Collaborations: January-September 1991

Collaborative Publications:

Dr. Paul Broome (BRL) and Dr. James Lipton (MSI/Cornell) presented a joint paper on "Constructive Relational Programming: A Declarative Approach to Program Corrections and High Level Optimization" at the Ninth Army Conference on Applied Mathematics and Computing.

Dr. Gerald Andersen (ARO) collaborated with Dr. James Glimm (MSI/Stony Brook) and with Mr. John Chiment (MSI/Cornell) on the MSI News article "ARO Fractal and Chaos Workshop" that appeared in MSI News 3(5): 4.

Mr. Donald Rollins (ARO) collaborated with Mr. John Chiment (MSI/Cornell) on the article "ARO Support of High School Science and Mathematics" that appeared in MSI News 3(4):7.

Collaborative Research:

Dr. Philip L.-F. Liu from the Cornell University School of Civil and Environmental Engineering is continuing his work with Dr. Zeki Demirbilek and Dr. Michael Briggs, both at the US Army's Waterways Experiment Station, Vicksburg, Mississippi. The group is investigating wave-current interactions in shallow water.

Dr. Subrata Mukhergee, Department of Theoretical and Applied Mechanics, Cornell University, and Dr. Peter C.-T. Chen, Benet Weapons Laboratory, Watervliet Arsenal, are continuing their cooperative work on the project "Sensitivities and Optimization Problems in Nonlinear Solid Mechanics."

Dr. J. T. Jenkins, Department of Theoretical and Applied Mechanics, Cornell University is working with Dr. T. W. Wright at the Ballistics Research Laboratory, Aberdeen MD. They are continuing joint research on the shattering of confine ceramics impacted by high velocity projectiles.

US ARMY attendance at MSI meetings:

Hybrid Systems Workshcp: June 10-12, 1991
Dr. Paul Broome (BRL)
Dr. Norman Coleman (ARDEC)
Mr. Robert Hein (Center for Signals Warfare)
Col. John James (TRADOC)

Probability Workshop: July 15-16, 1991
Dr. Gerald Andersen (ARO)

Combinatorics and Discrete Geometry Workshop: July 17-20, 1991
Dr. Paul Broome (BRL)
Dr. Kenneth Clark (ARO)

NB: Army researchers were also in attendance at the MSI-cosponsored **First International Workshop on Logic Programming and Nonmonotonic Reasoning**, held July 22-24, 1991 in Washington, DC. However, records of attendance are not available at MSI.

MSI/Cornell and MSI/Stony Brook attendance at US ARMY meetings:

ARO/Uni. of Pennsylvania Meeting: March, 1991
Dr. Anil Nerode (MSI/Cornell)

ARO Fractal and Chaos Workshop: May 21-23, 1991
Dr. James Glimm (MSI/Stony Brook)
Dr. John Guckenheimer (Cornell)

Ninth Army Conference on Applied Mathematics and Computing: June 18-21, 1991
Mr. Bruce Anderson (Cornell)
Dr. Adam Bojanczyk (Cornell)
Dr. Maria Bonacina (Stony Brook)

Mr. Yuefan Deng (Stony Brook)
Dr. Keith Dennis (Cornell)
Mr. Devdatt P. Dubhashi (Cornell)
Dr. James Glimm (MSI/Stony Brook)
Dr. John Grove (MSI/Stony Brook)
Mr. Jieh Hsiang (Stony Brook)
Mr. Tong J. Lee (Cornell)
Dr. James Lipton (MSI)
Dr. Franklin Luk (Cornell)
Ms. Alyson Reeves (Cornell)
Dr. Allan Steinhardt (Cornell)
Dr. Ram P. Srivastav (Stony Brook)
Dr. Moss Sweedler (MSI/Cornell)
Mr. Yi Wang (Stony Brook)
Mr. Qiang Zhang (Stony Brook)

Miscellaneous Army Assistance:

Dr. D. A. Caughey (Cornell) facilitated use of the Cornell Supercomputer facility by researchers from the Natick Laboratory RD&E Center. (February 1991)

Dr. N. U. Prabhu (Cornell) assisted Dr. Philip E. Wralstad (TEXCOM) in the analysis of time-independent failure models. (May 1991)

MSI staff assisted Mr. Richard Poisel (Center for Signals Warfare) in the distribution of materials on current Center for Signals Warfare research at the MSI Hybrid Systems Workshop. (May 1991)

Mr. John Chiment (MSI/Cornell) assisted Dr. Edward Perry (Waterways Experiment Station) in locating current texts on statistics. (June 1991)

Mr. Hugh Gauch (Cornell) and Mr. John Chiment (MSI/Cornell) assisted Dr. Robert L. Helmbold in locating current computer software for hierarchical data clustering. (June 1991)

Mr. Michael Woodall (Cornell Math. Library) and Mr. John Chiment (MSI/Cornell) assisted Mr. Robert Hein (Center for Signals Warfare)

in conducting a computerized search of the European literature on Zhegalkin algebras. (July-August 1991)

Technical Reports:

Copies of MSI technical reports, including reports prepared by visiting Army researchers, were distributed to ARO and academic libraries as they were produced and to individual researchers as requested.

MSI TECHNICAL REPORTS 1986

1. THE EFFECT OF STRUCTURE ON THE STABILITY OF DETONATIONS
I. ROLE OF THE INDUCTION ZONE
J.D. BUCKMASTER, G.S.S. LUDFORD
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